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Adaptive Shape Parameterization for Aerodynamic Design

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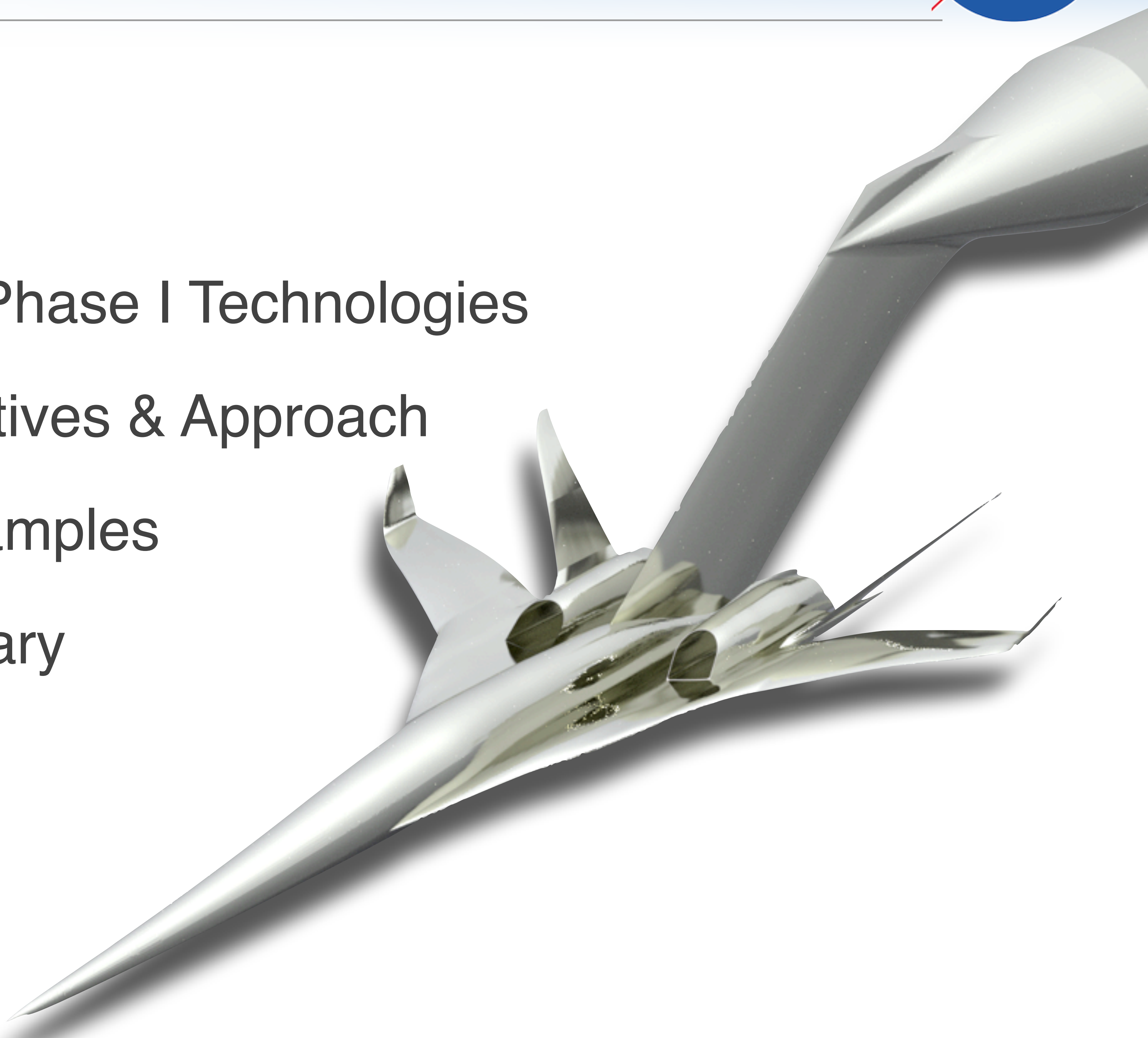
Motivation

Goal: Use tools developed in the last two decades to dramatically simplify and automate aerodynamic shape design

- **Reduce labor** for setup of design and geometric manipulation to automate and streamline design process
- **Automate** to reduce dependence on designer expertise
- **Capitalize on** two decades of explosive growth in computer graphics and 3D modeling
- **Capitalize on** over a decade of investment in sensitivity analysis, adjoint solvers and computational power

Outline

- Background
- Applications of Phase I Technologies
- Technical Objectives & Approach
- Results and Examples
- Status & Summary



Phase I Technologies

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1. Introduced Parametric control of discrete geometry

   Plugins for leveraging modern CG and 3D modeling tools

   Constraint-based deformation

2. On-the-fly re-parameterization

   Introduce finer-scale shape control as needed to advance objective

3. Automated shape parameter selection

   Capture and exploit sensitivity information as the design evolves

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Parametric control of discrete geometry

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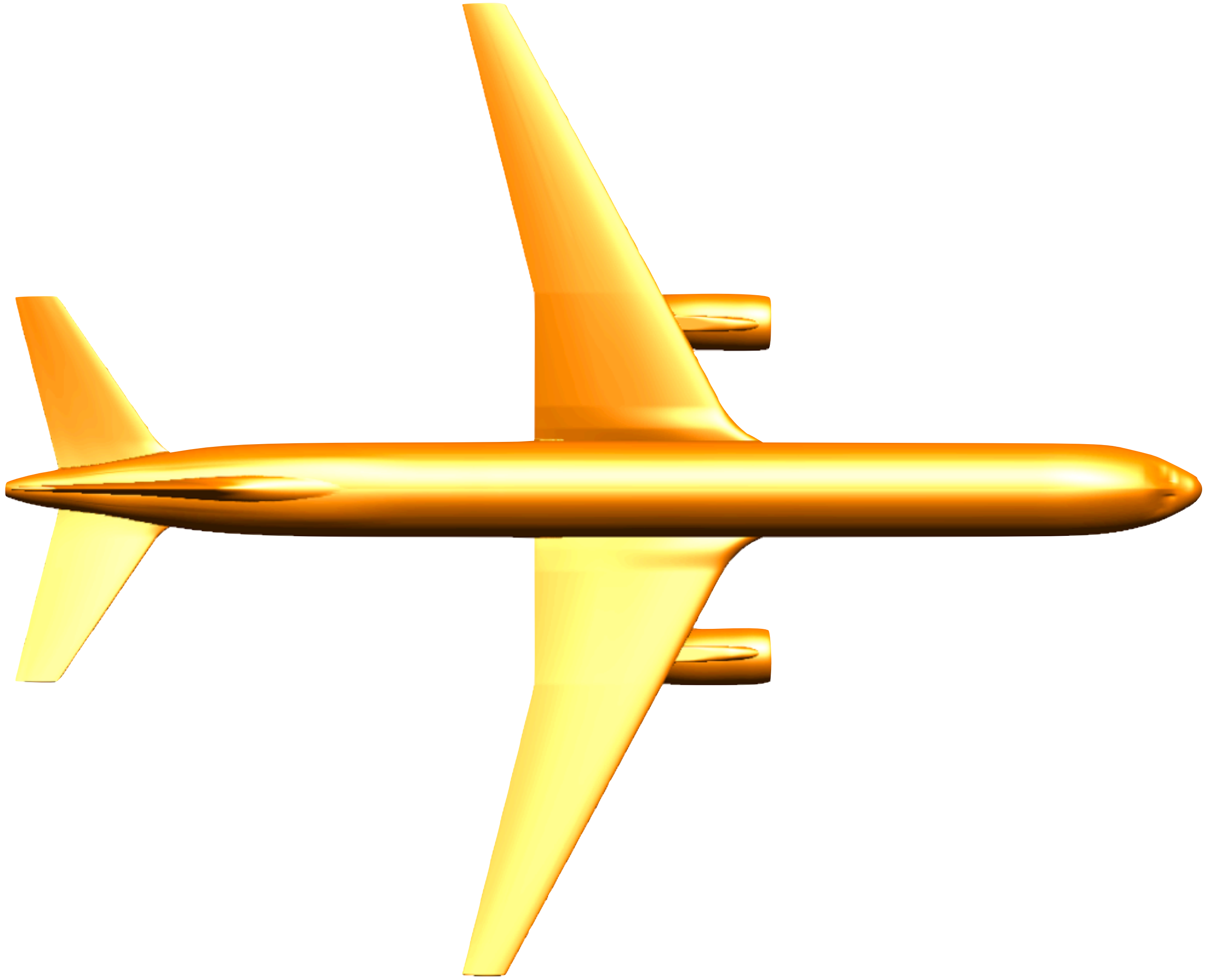

Discrete model of Generic Transport Configuration

Phase I Technolog

Innovations in Phase I

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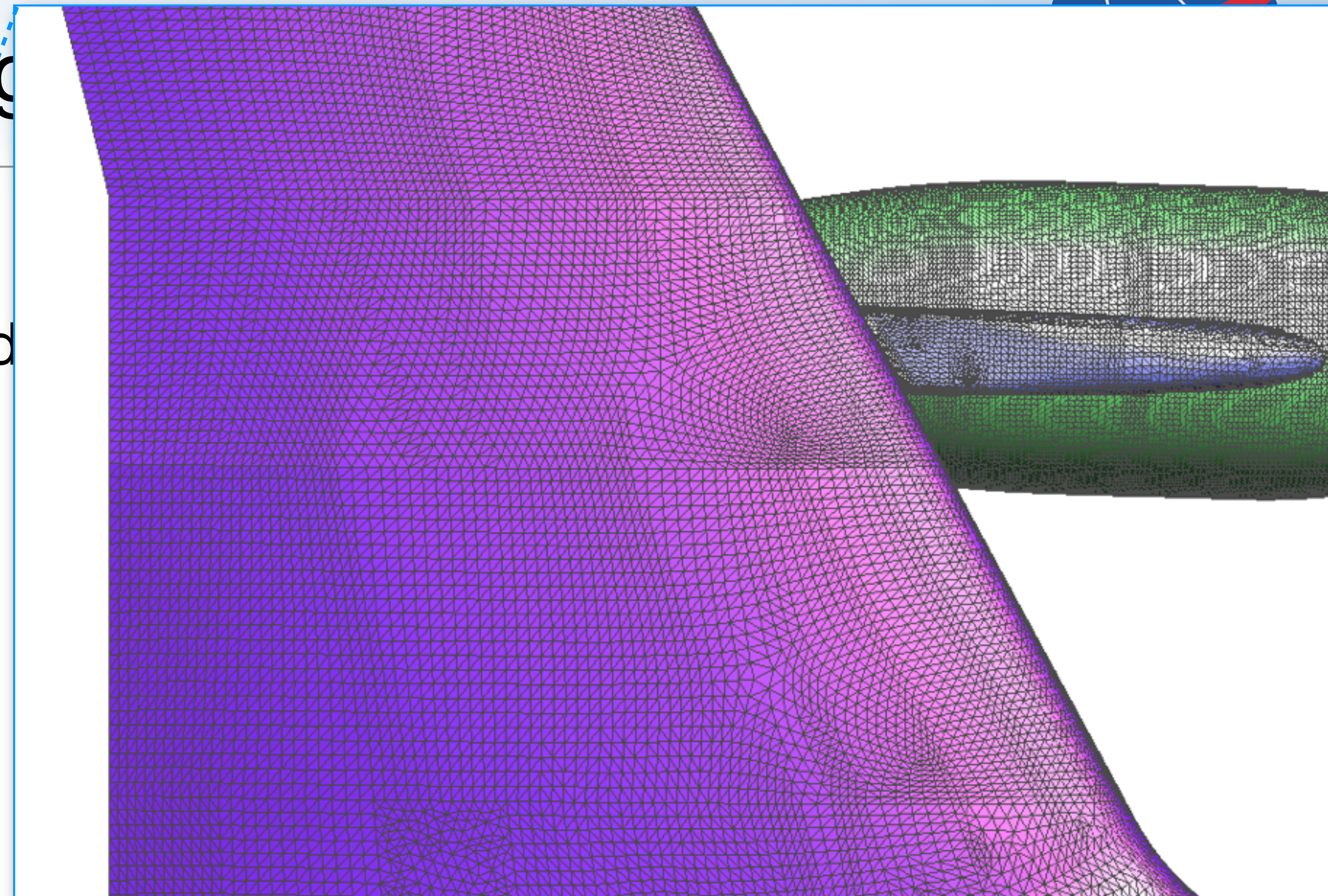

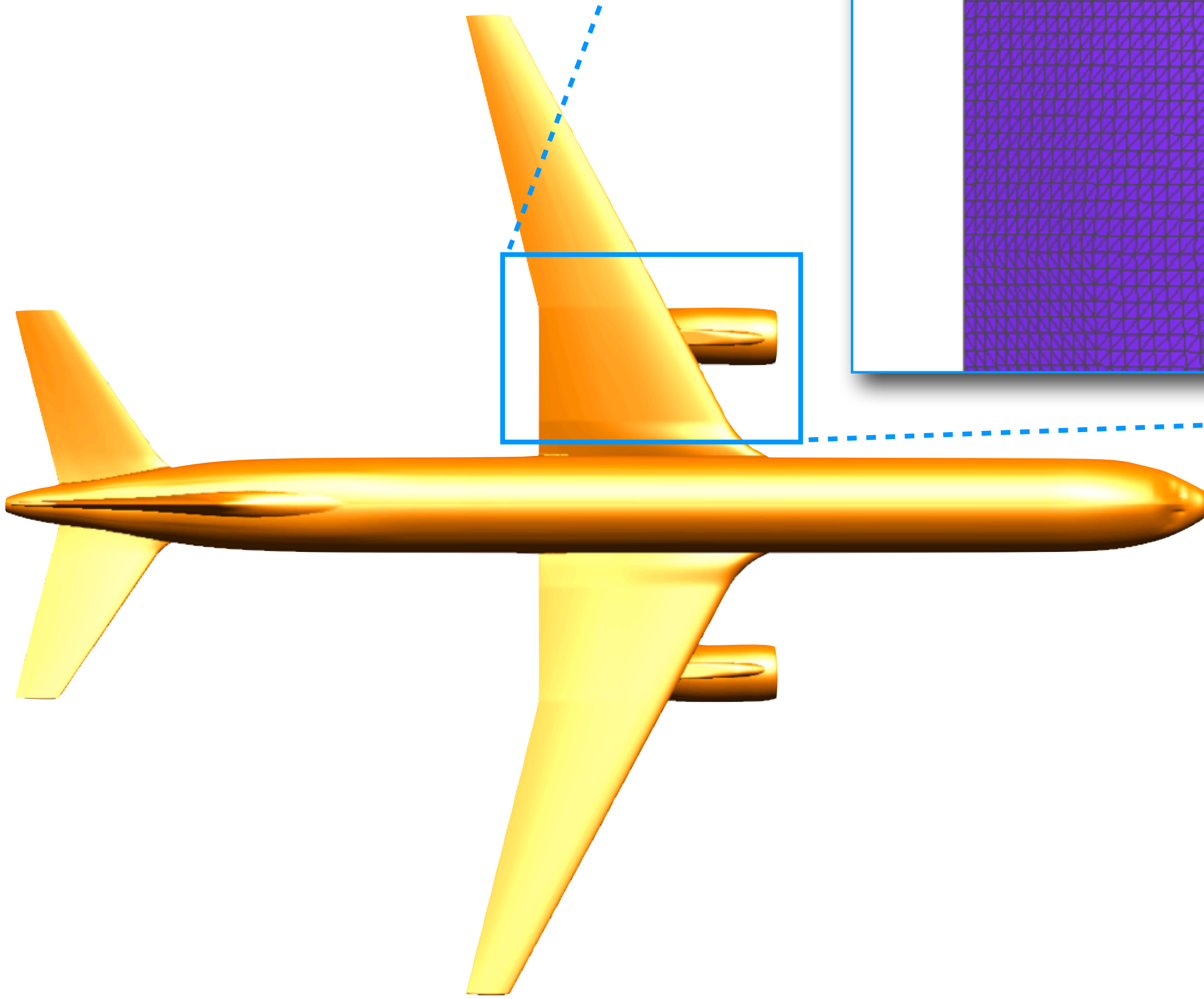

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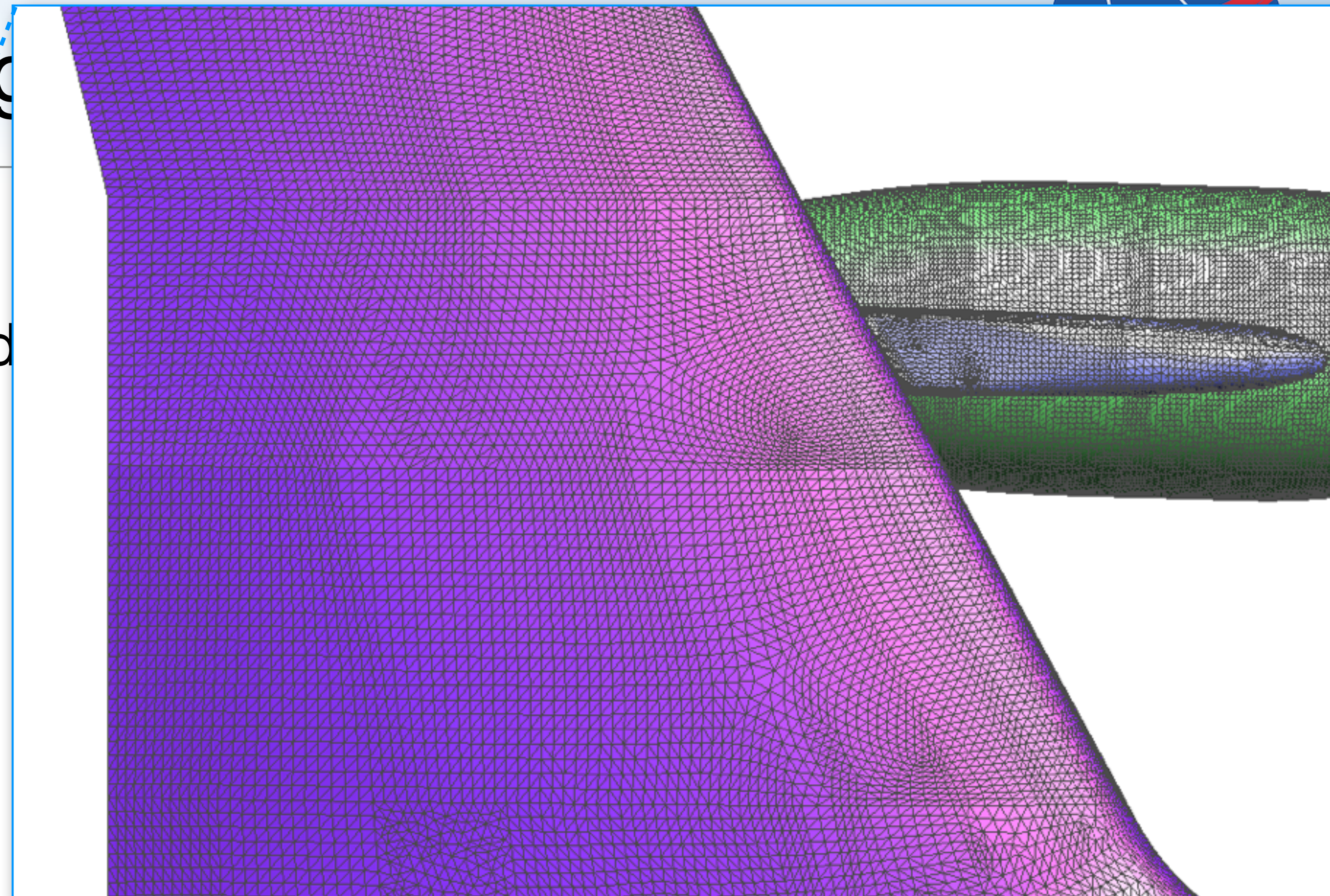
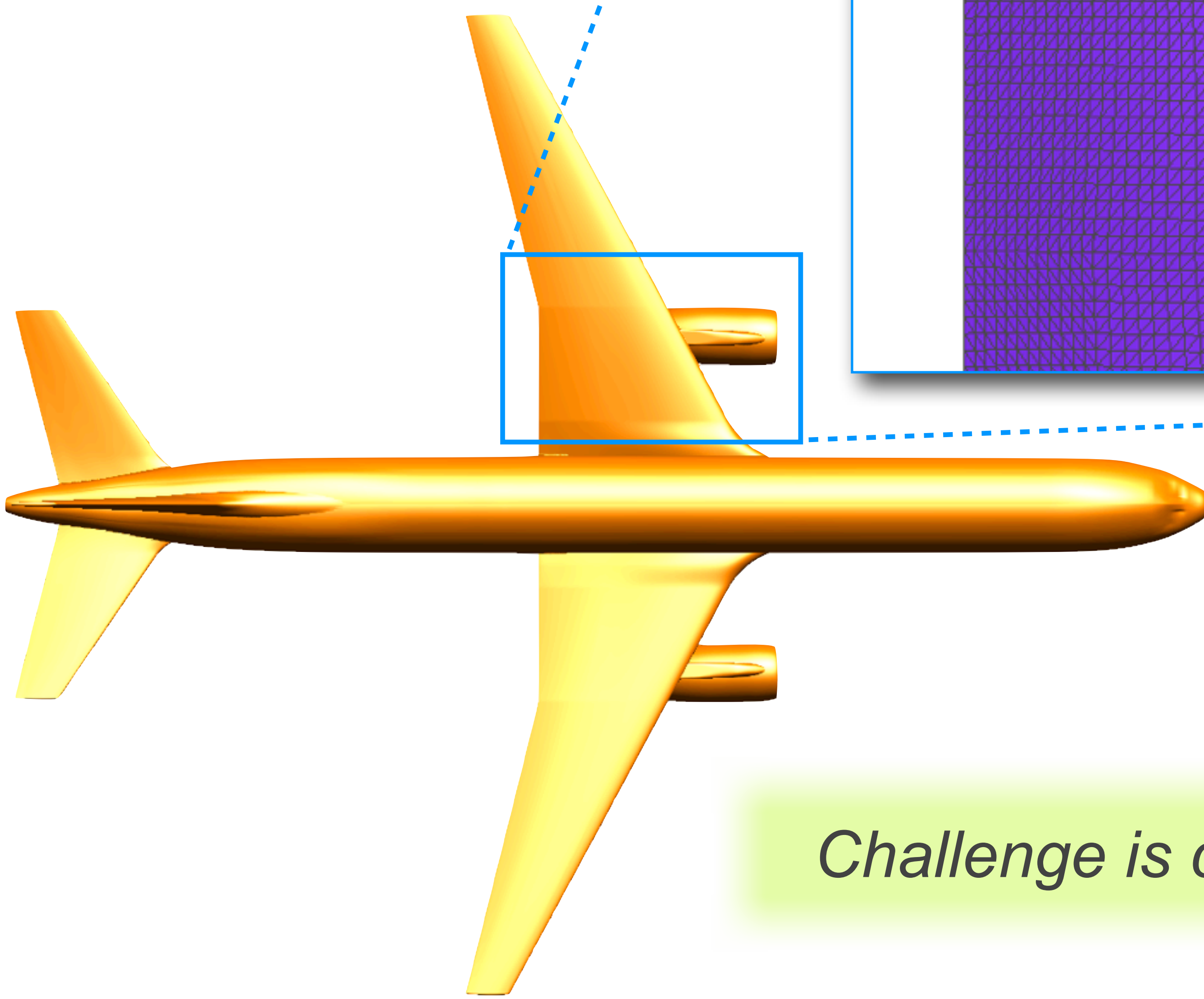




Discrete model of Generic Transport Configuration

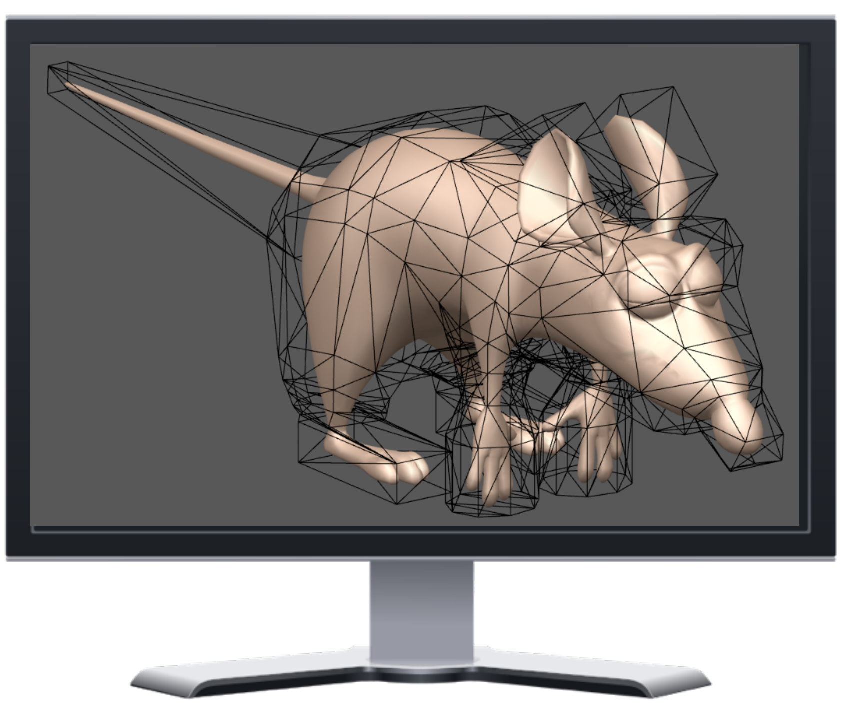
Challenge is coordinated parametric manipulation

Phase I Technologies

Innovations in Phase I work addressed this fundamental challenge

Parametric control of discrete geometry

Similar situation in CG industry



Discrete model of input geometry

$50B industry with extremely rich toolsets for shape manipulation

Phase I Technologies

Innovations in Phase I work addressed thi

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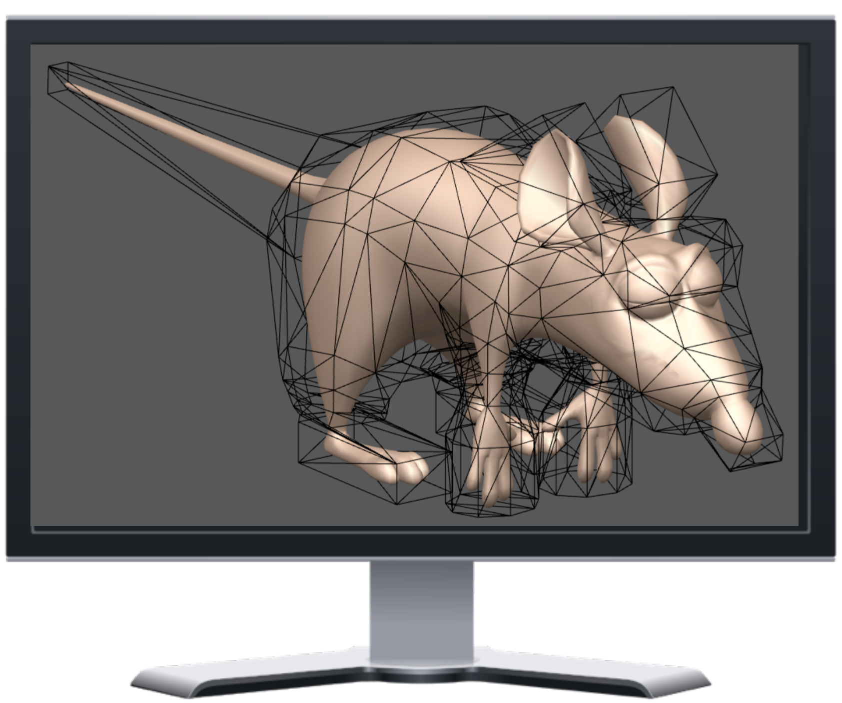
Similar situation in CG industry



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Phase I Technologies

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Skeletal deformation of
Generic Transport

- *AIAA 2009-0965* “Parametric Deformation of Discrete Geometry for Aerodynamic Shape Design”, 2009
- *ICCFD7-#2001, "Constraint-based Shape Parameterization for Aerodynamic Design", 2012*

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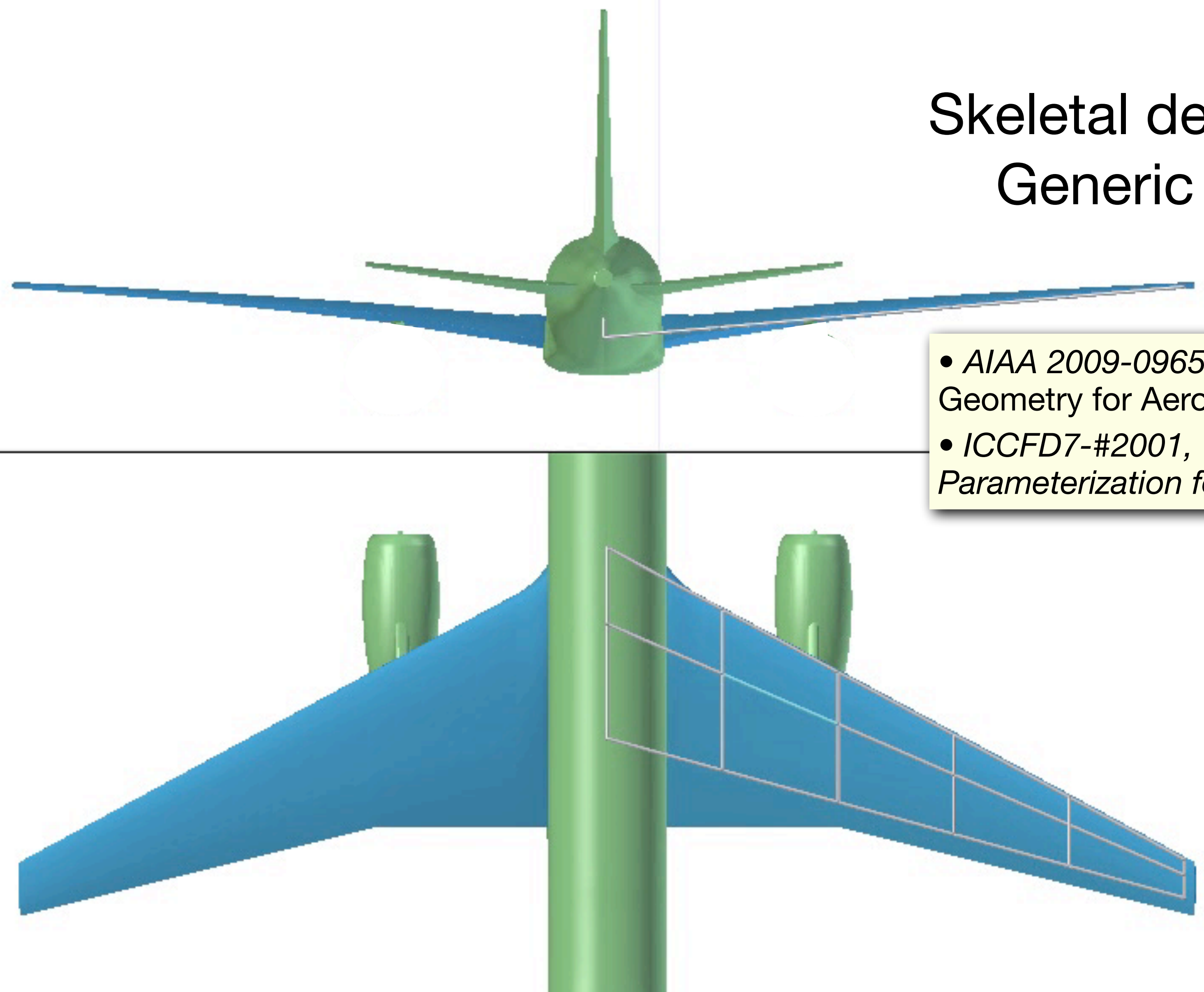

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Phase II Work

Extend parametric control of discrete geometry

1. Developed discrete geometry platform for aerospace design

   Scriptable specialized plugins for

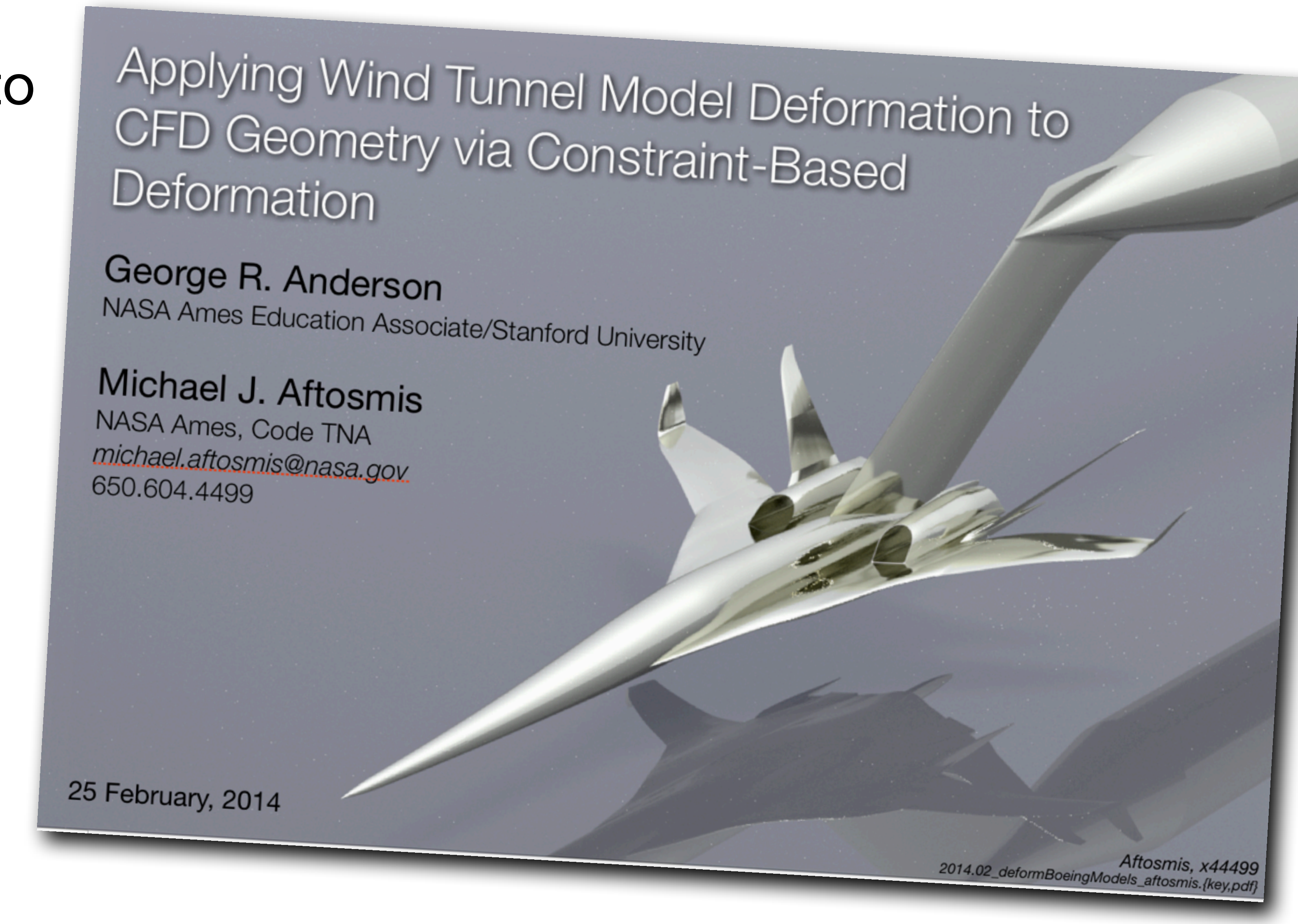
   - *Wing-twist & structural bending*
   - *Skeletal deflection of control surfaces*
   - *Constraint-based deformation & airfoil shape control*
   - *Hierarchical linking of parameters through configurations*
   - *Analysis parameters (volume, thickness etc..)*

Mature through direct application to problems in NASA's aeronautics mission

ARMD Applications of Seedling Investment

Support High Speed Research Project 3.0, High Fidelity Analysis & Validation (HiFAV)
T3.3.2 – Develop/refine CFD for Full Vehicle
- **33213** "Evaluate Boeing N+2 Phase II Boom Model with aeroelastic deformations" - Milestone due 30 March, 2014

Sensitivity of boom signature to aeroelastic deformation



- Application of constraint-based deformation
- Exercised methods prototyped in Phase I in engineering environment with realistically complex geometry
- Applied deformations measured in wind-tunnel to CFD model and compared near-field pressure signatures of the rigid and deformed geometry.

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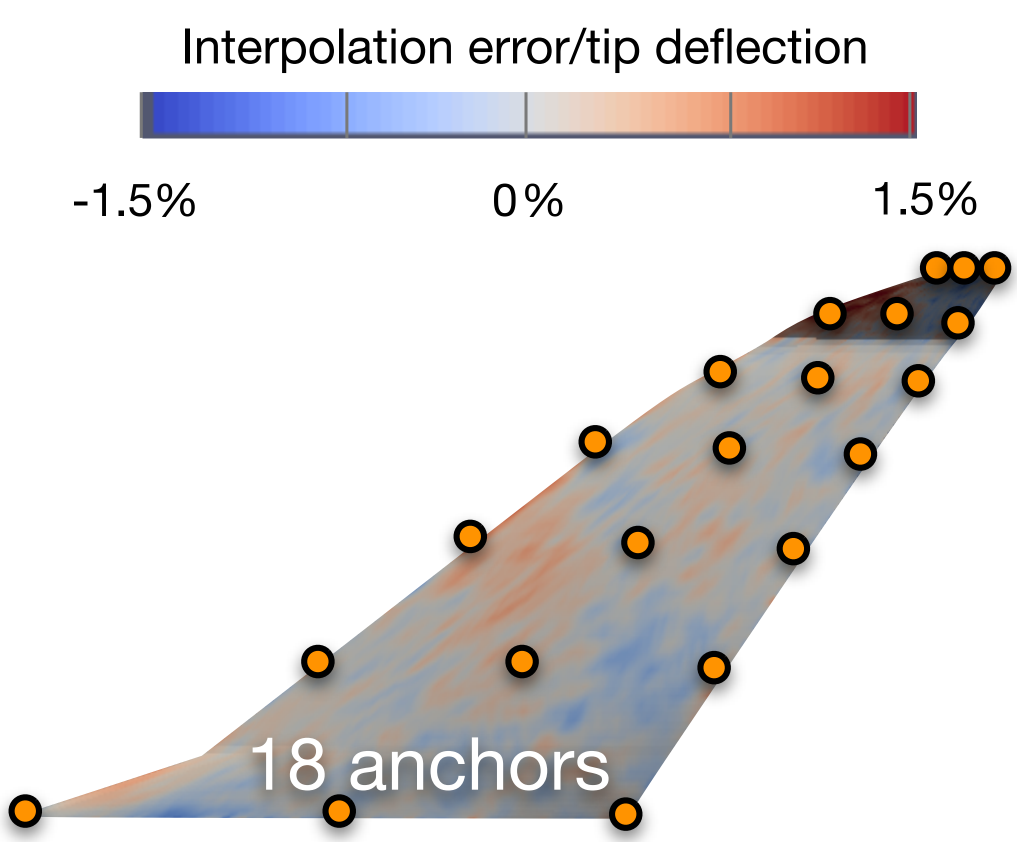
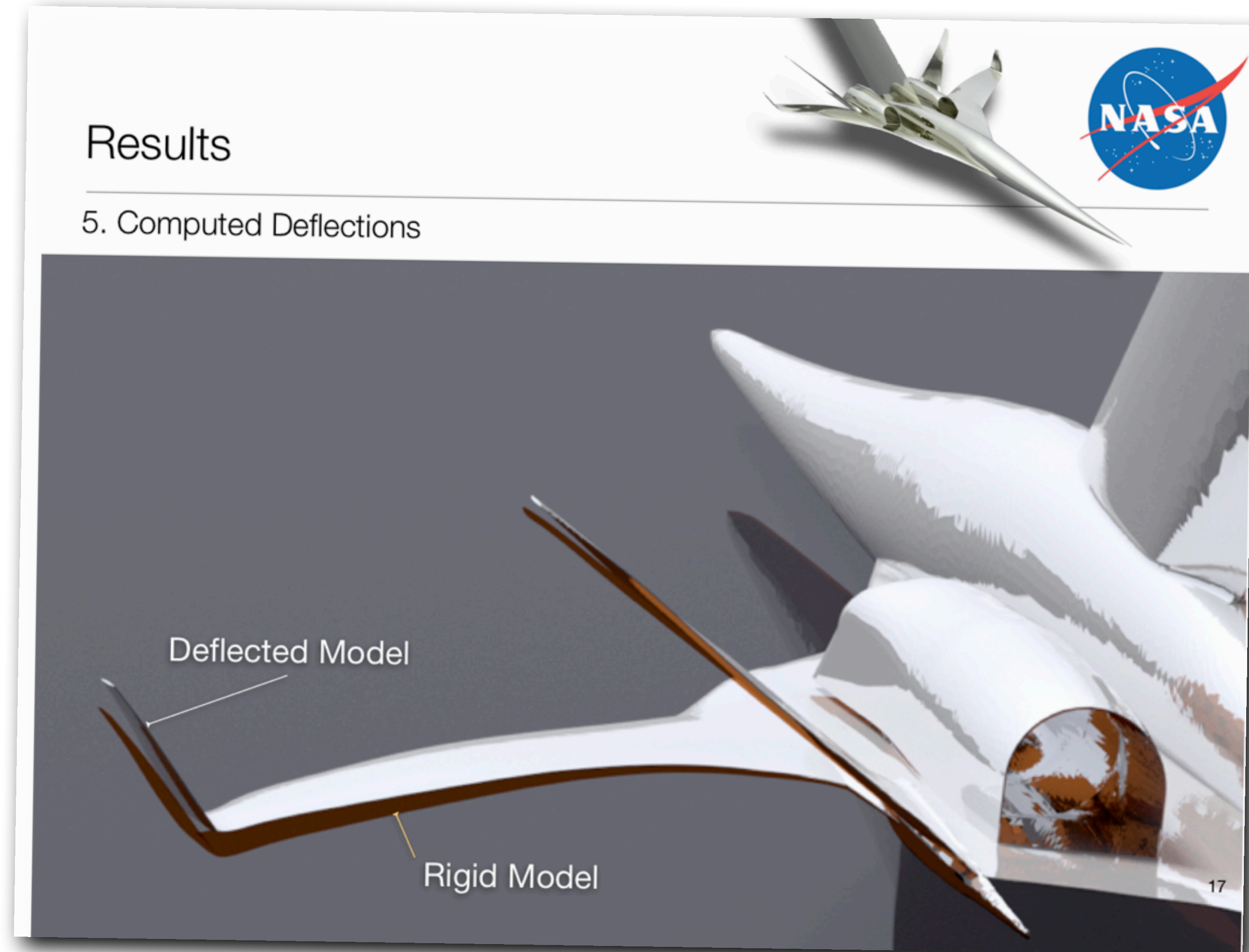




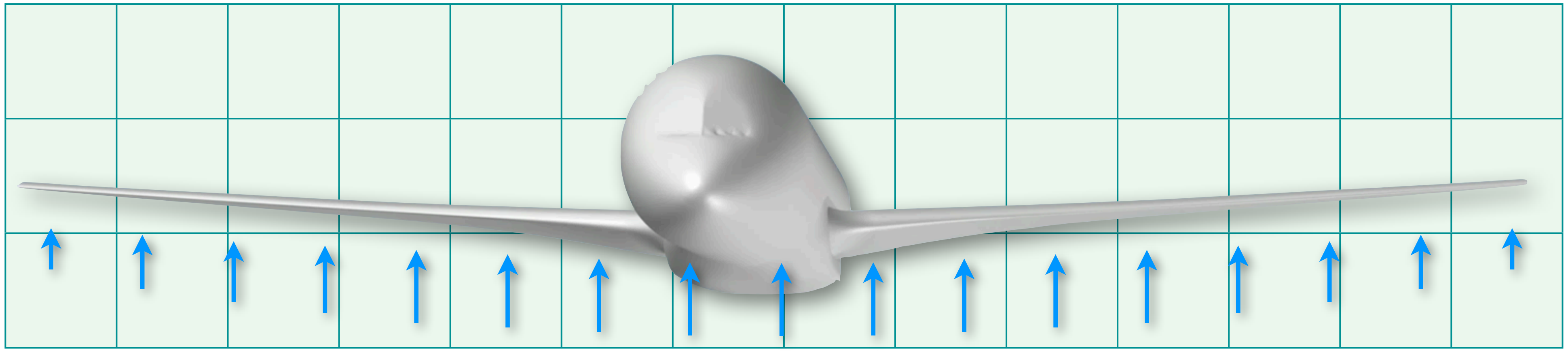
- Proof-of-Concept: Constraint-based deformation using 18-32 anchors recovered model shape to within the accuracy of the laser scan
- Computations on deformed model was used to quantify effects of aeroelastic deformation on boom footprint – directly supporting the program milestone

ARMD Applications of Seedling Investment

Support Milestones for FA Fixed-Wing & Advanced Air Transport Technology Project
2103-2014 – Elastic Aircraft Initiative & Variable Camber Continuous Trailing Edge Flap (VCCTEF)
TC2.1 – Higher Aspect Ratio Optimal Wing and Performance Adaptive Aeroelastic Wing

Elastically-Shaped Aircraft

- Plugins from Phase I underlie coupled aero-structural solver being used to support several tasks in the AATT Project



• *AIAA 2014-0836, "Static Aeroelastic Analysis with an Inviscid Cartesian Method", Jan. 2014*

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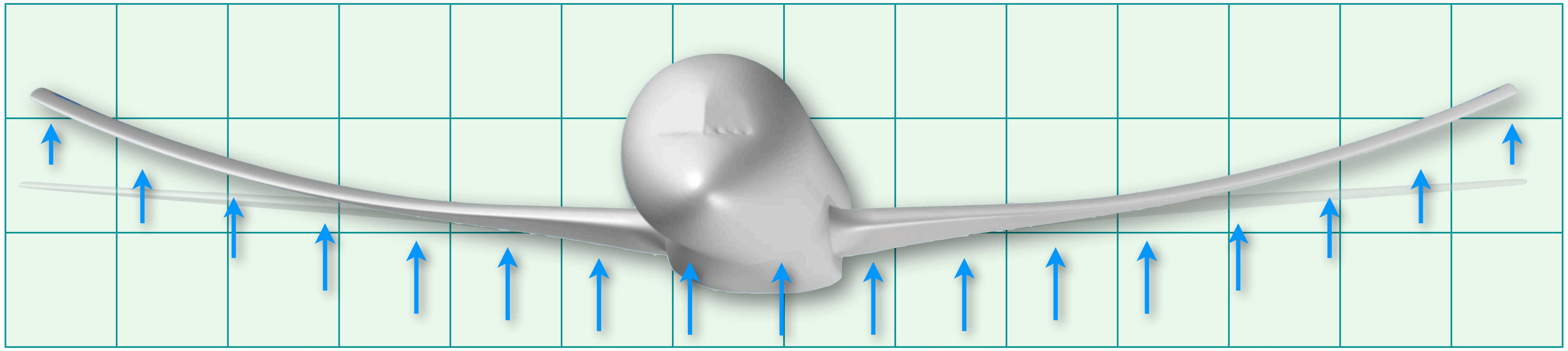

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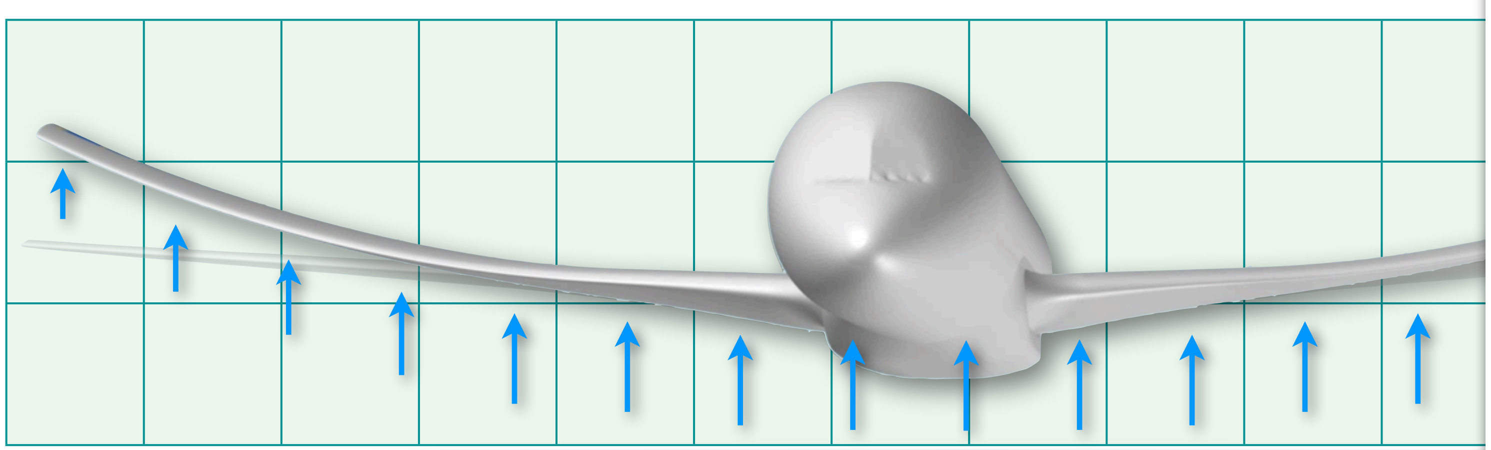

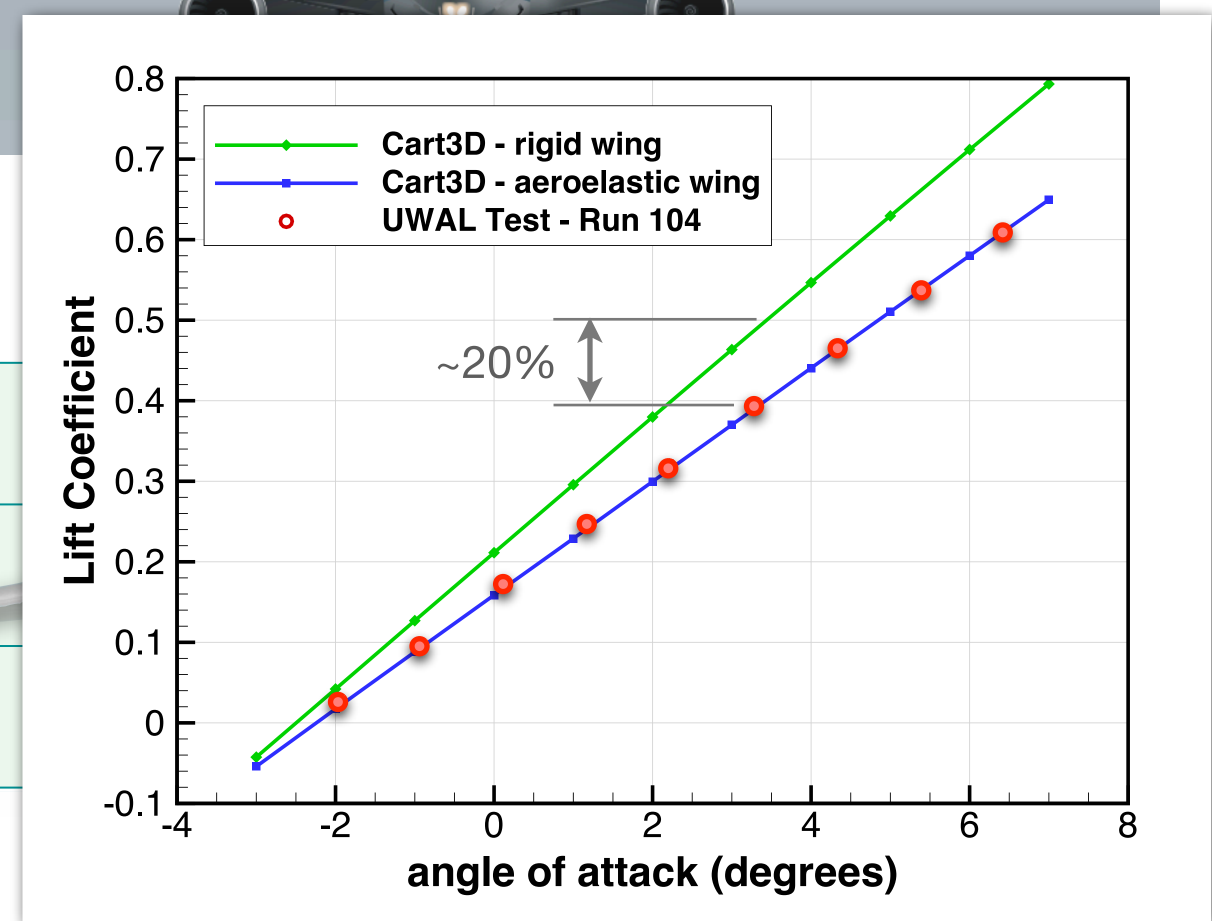

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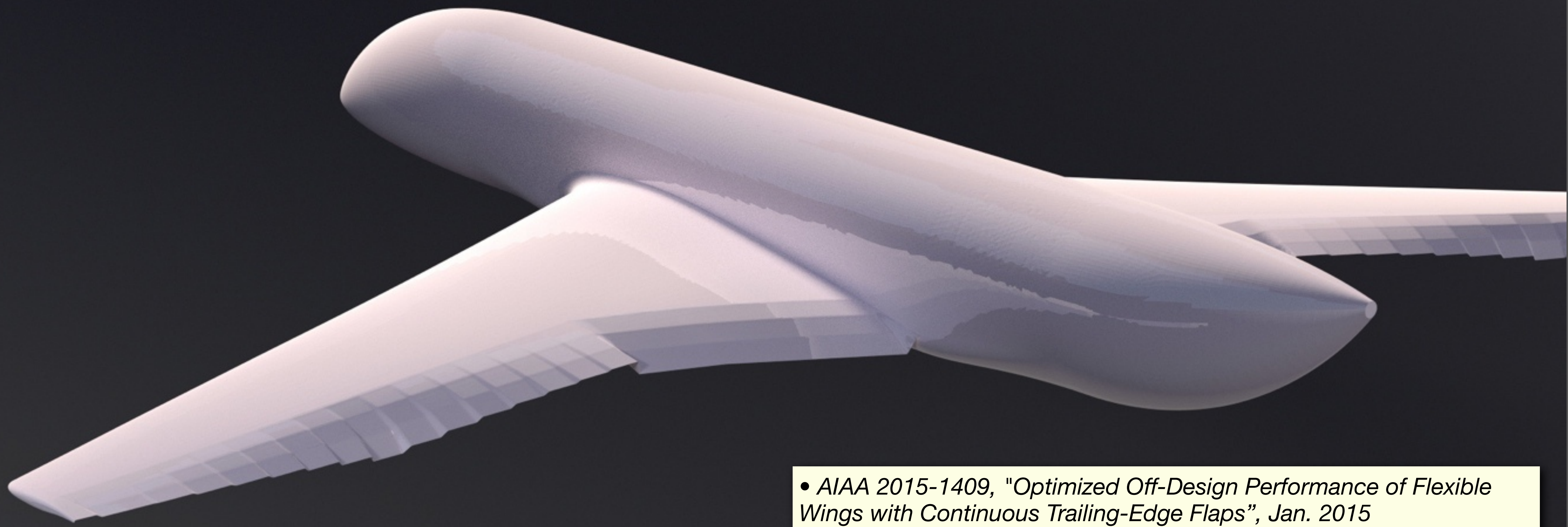
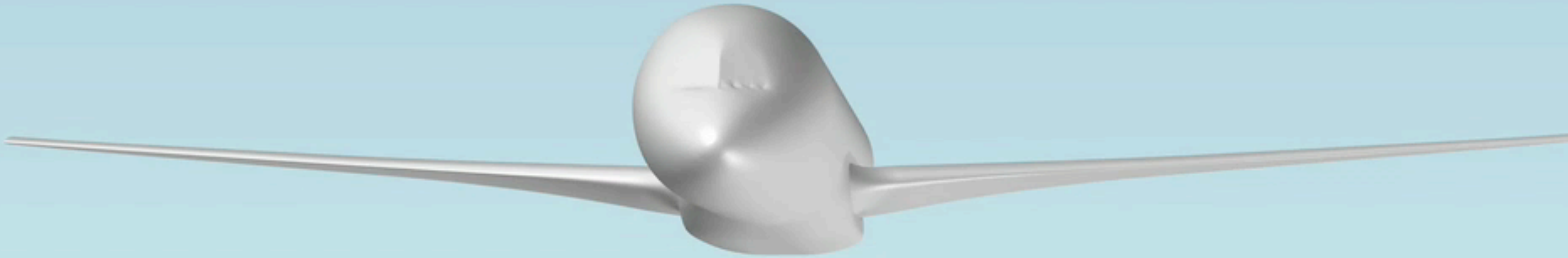
- Blender plugins for parametric skeletal deformation used to deflect the 14x3-segment VCCTEF being studied under PAAW



• AIAA 2015-1409, "Optimized Off-Design Performance of Flexible Wings with Continuous Trailing-Edge Flaps", Jan. 2015

- Deflect 14 flaps with 3 segments each & elastomer in-between
- Wing deforms due to aerodynamic loading
- Simultaneously optimize flap deflection and twist at fixed-lift to determine the optimal jig-shape wing



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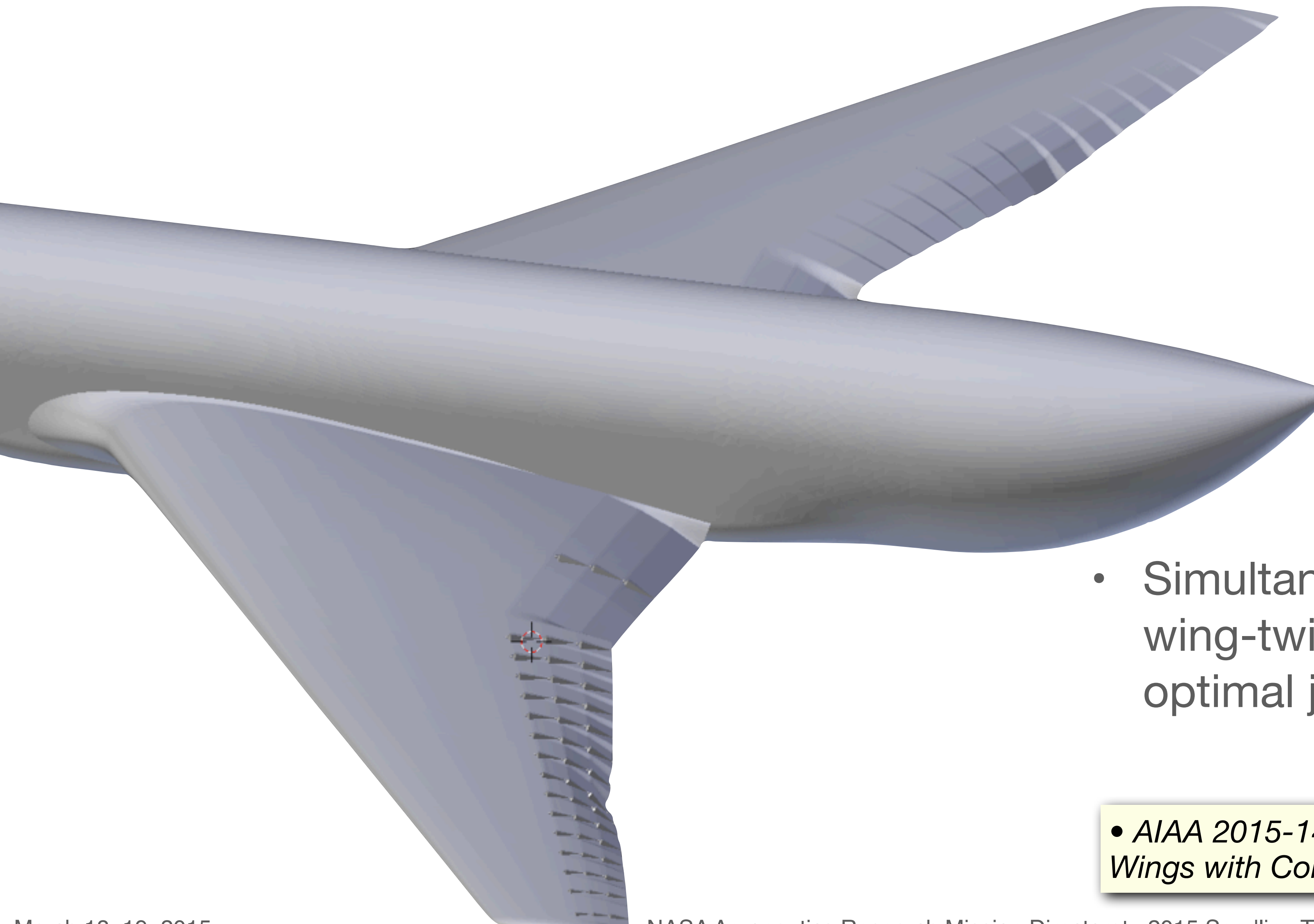

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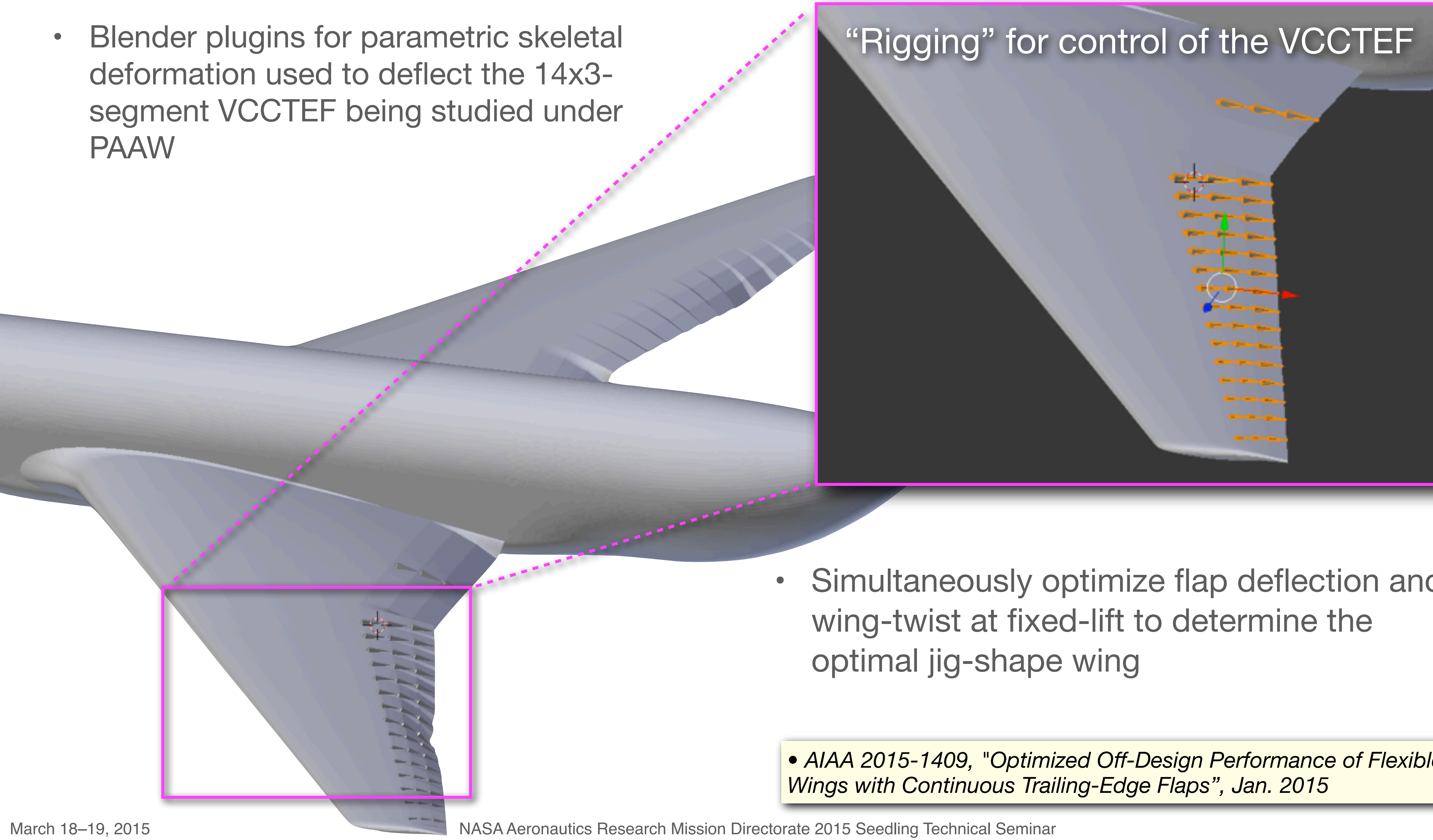

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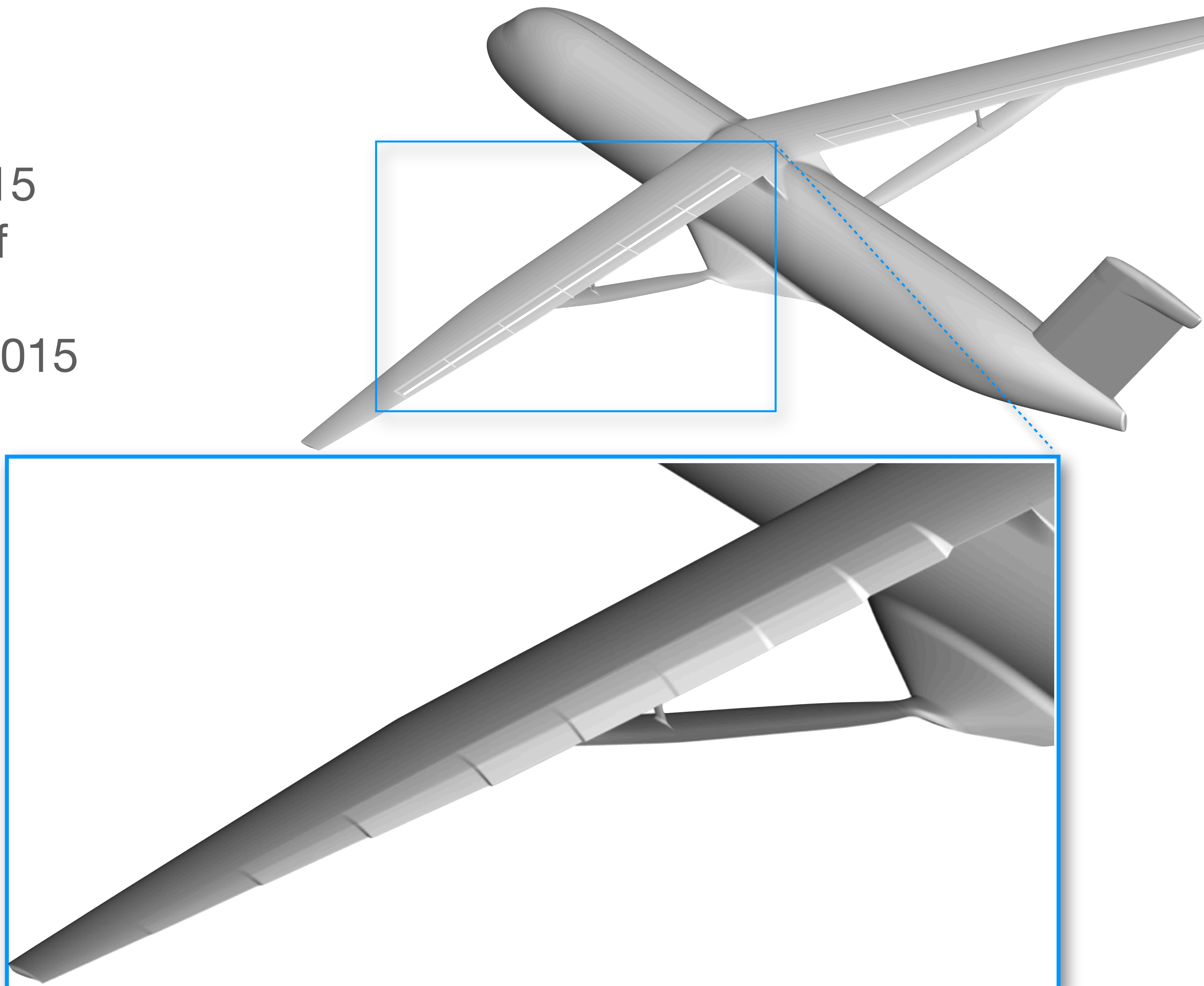
- Similar deformation and flap-rigging being used to meet FY15 L3 Milestone for assessment of the VCCTEF on the the Truss Braced Wing configuration in 2015



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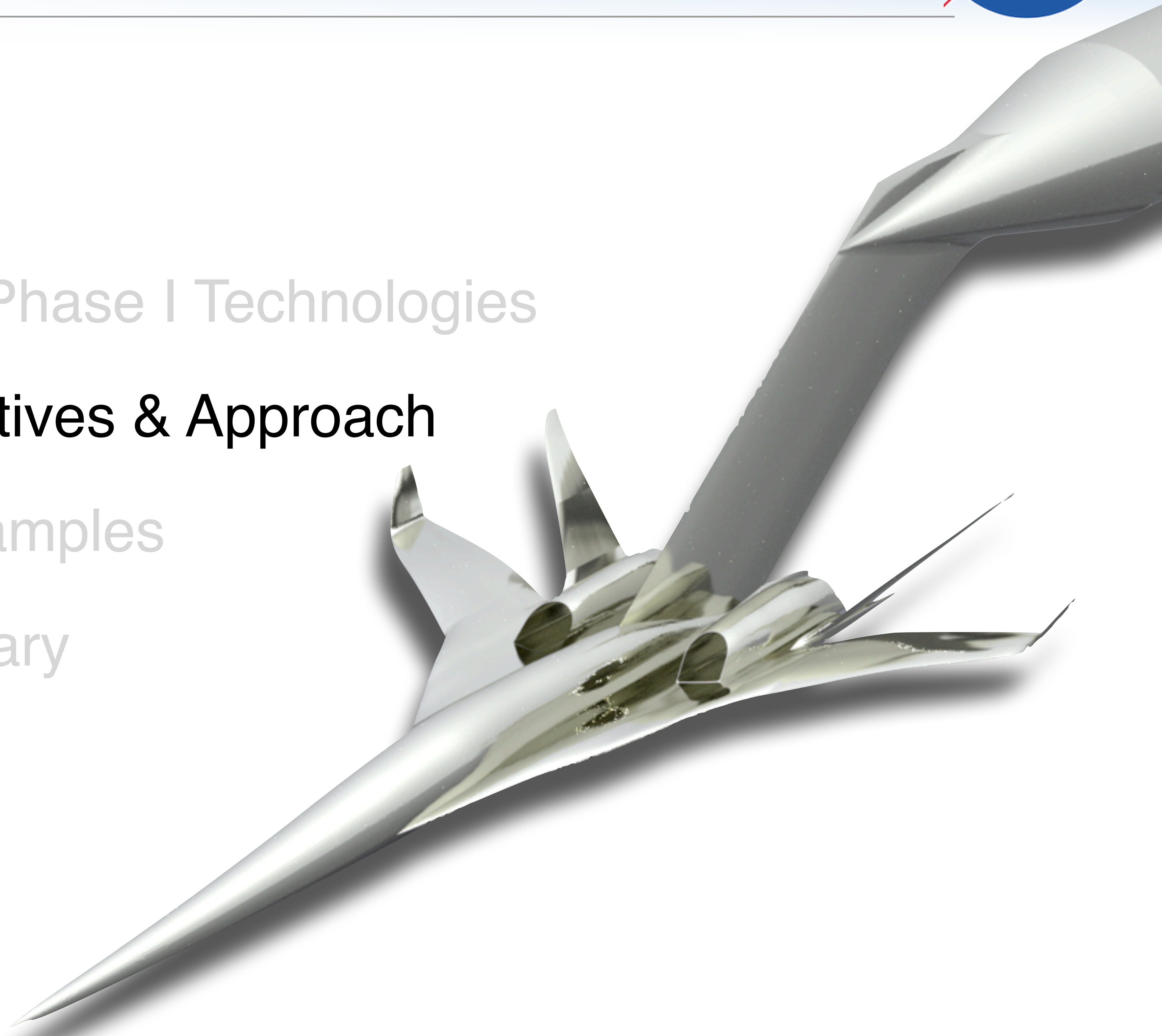


Technical Approach

✓ Parametric control of Discrete Geometry

- Progressive shape parameterization

  Efficiently approach optimum of continuous problem

- Automatic adaptive shape control

  Automatically increase fidelity – reduce dependence on designer skill

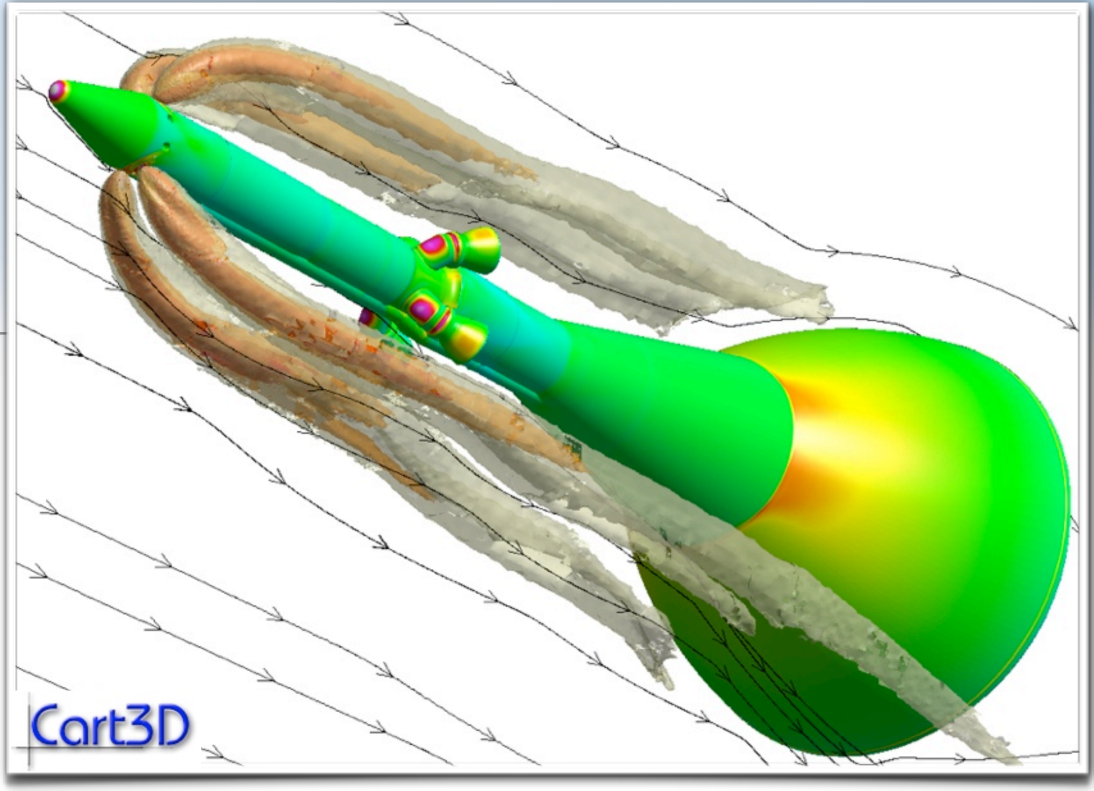
  Adjoint-based sensitivity information

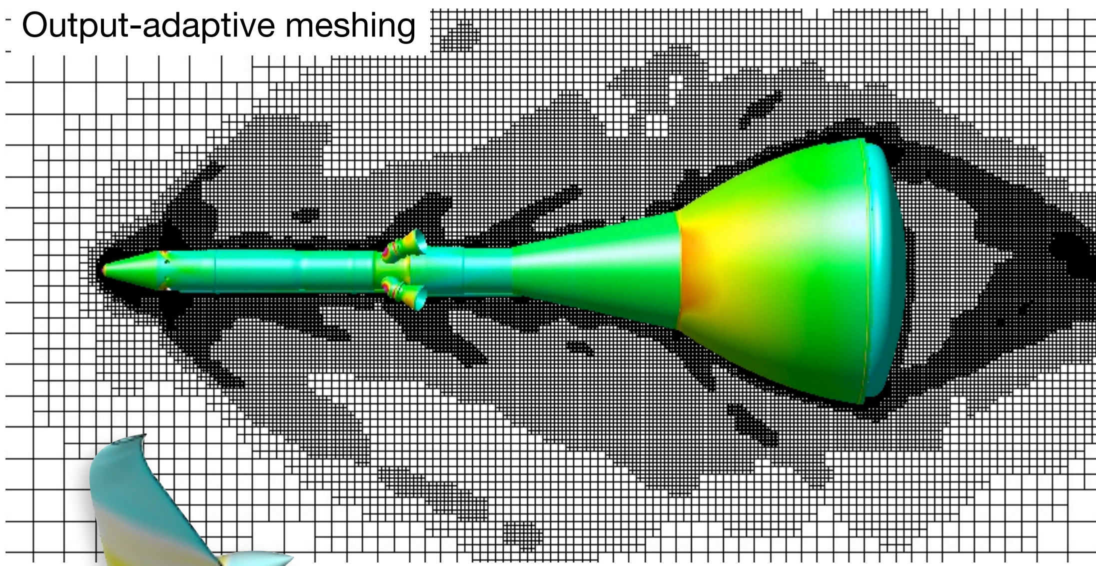
  Accelerate design

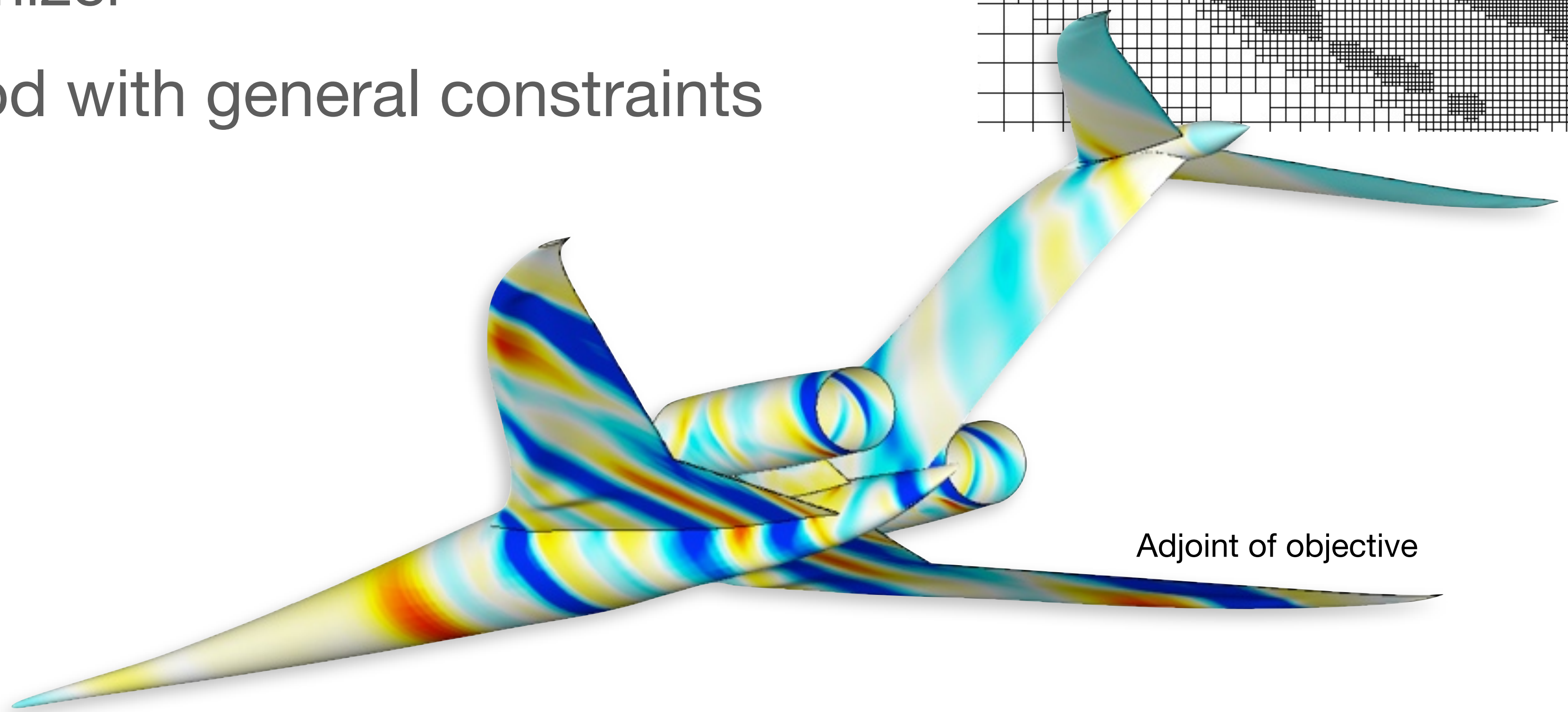
Technical Approach

Cart3D Design Framework

- Cartesian cut-cell method with automated meshing of complex configurations
- Inviscid solver with adjoint-driven
  - Adaptive meshing for error control
  - Objective and constraint gradients
- SNOPT Optimizer
  - SQP method with general constraints







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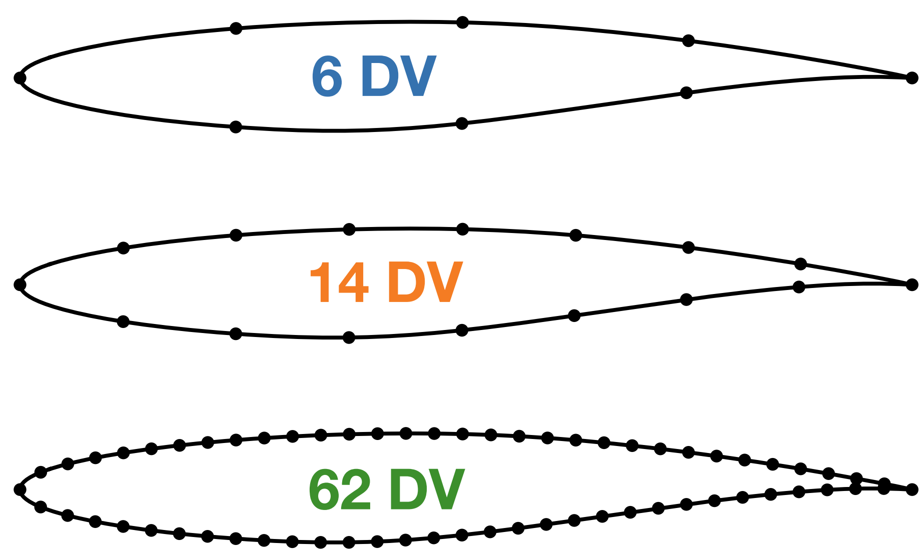
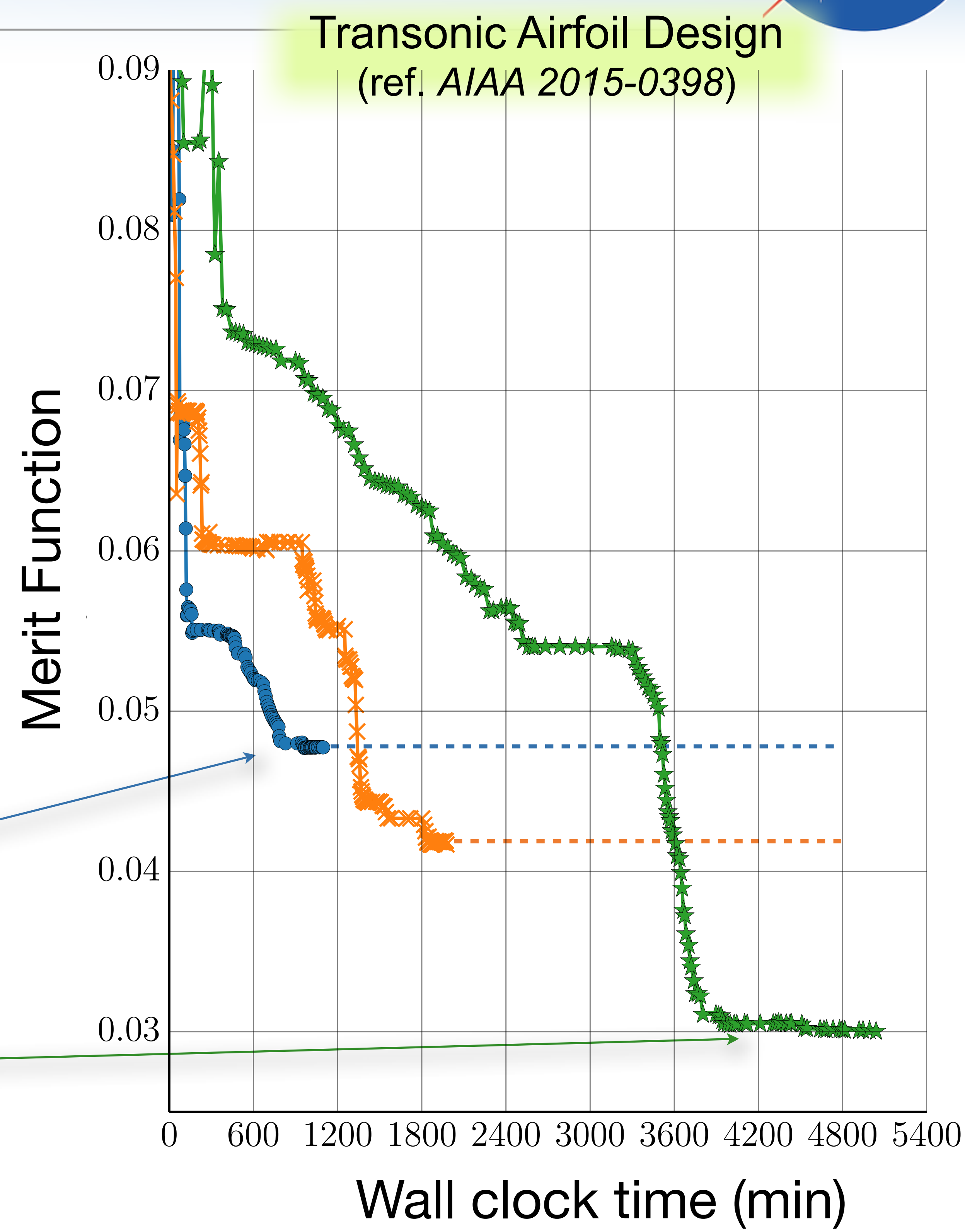
Static Parameterization

- Consider 3 *static* parameterizations



6 DV: Low-fidelity control
Faster design improvement

62 DV: High-fidelity control
Better final design

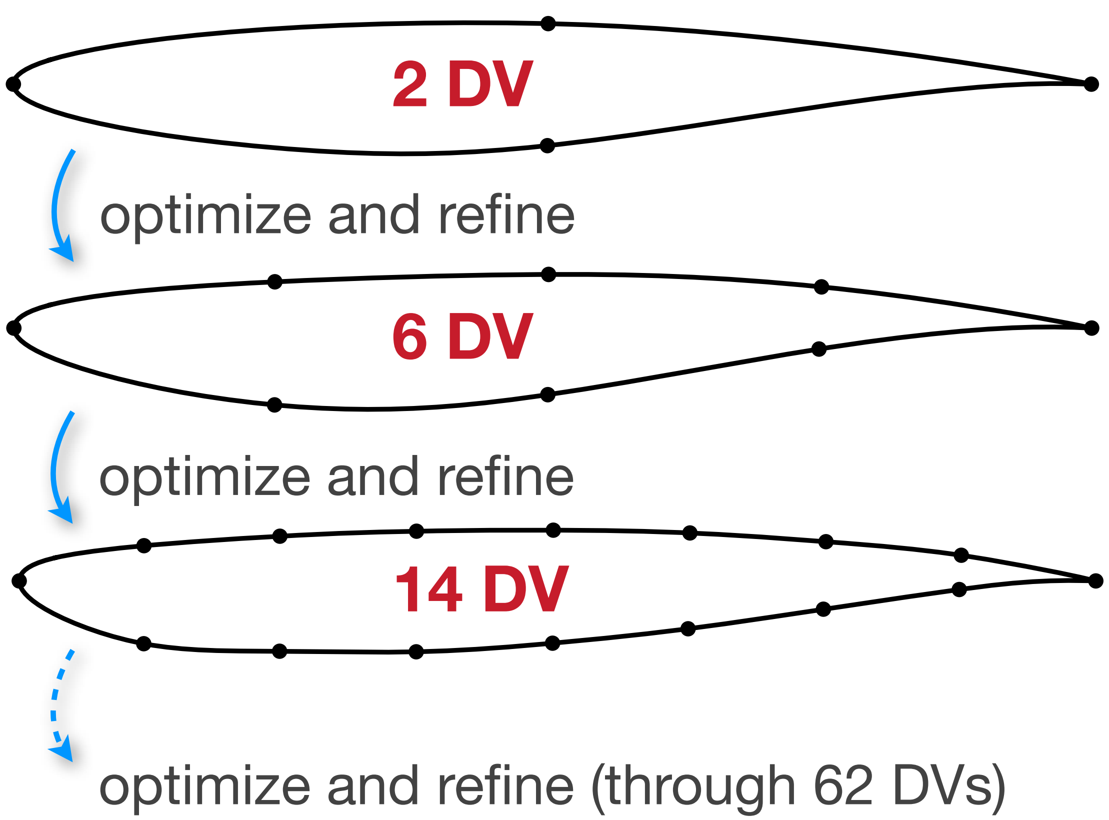


Plotted at major search iterations, on 20 Ivy-bridge cores

Technical Approach

Progressive Parameterization

- Increase fidelity of control as design progresses



- Fast initial improvement – while still approaching continuous shape control

- *AIAA 2015-0398 “Adaptive shape control for aerodynamic design”, 2015*

Technical Approach

Progressive Parameterization

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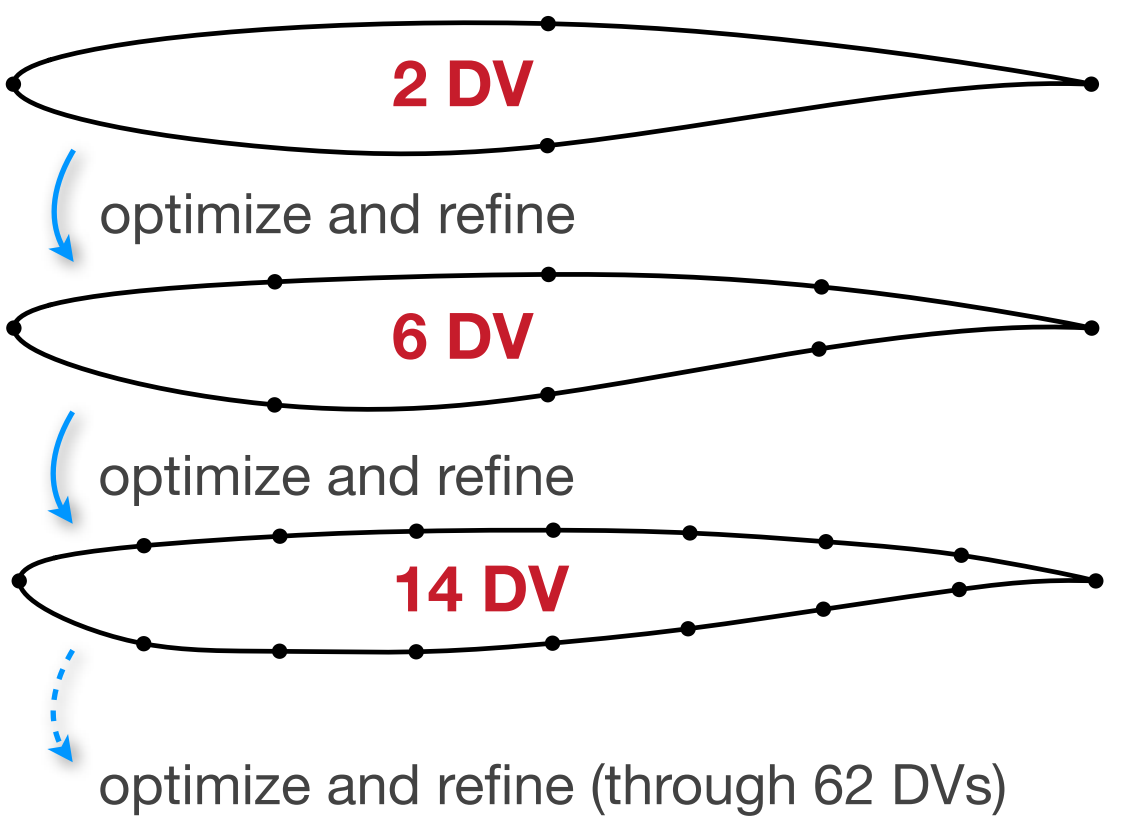

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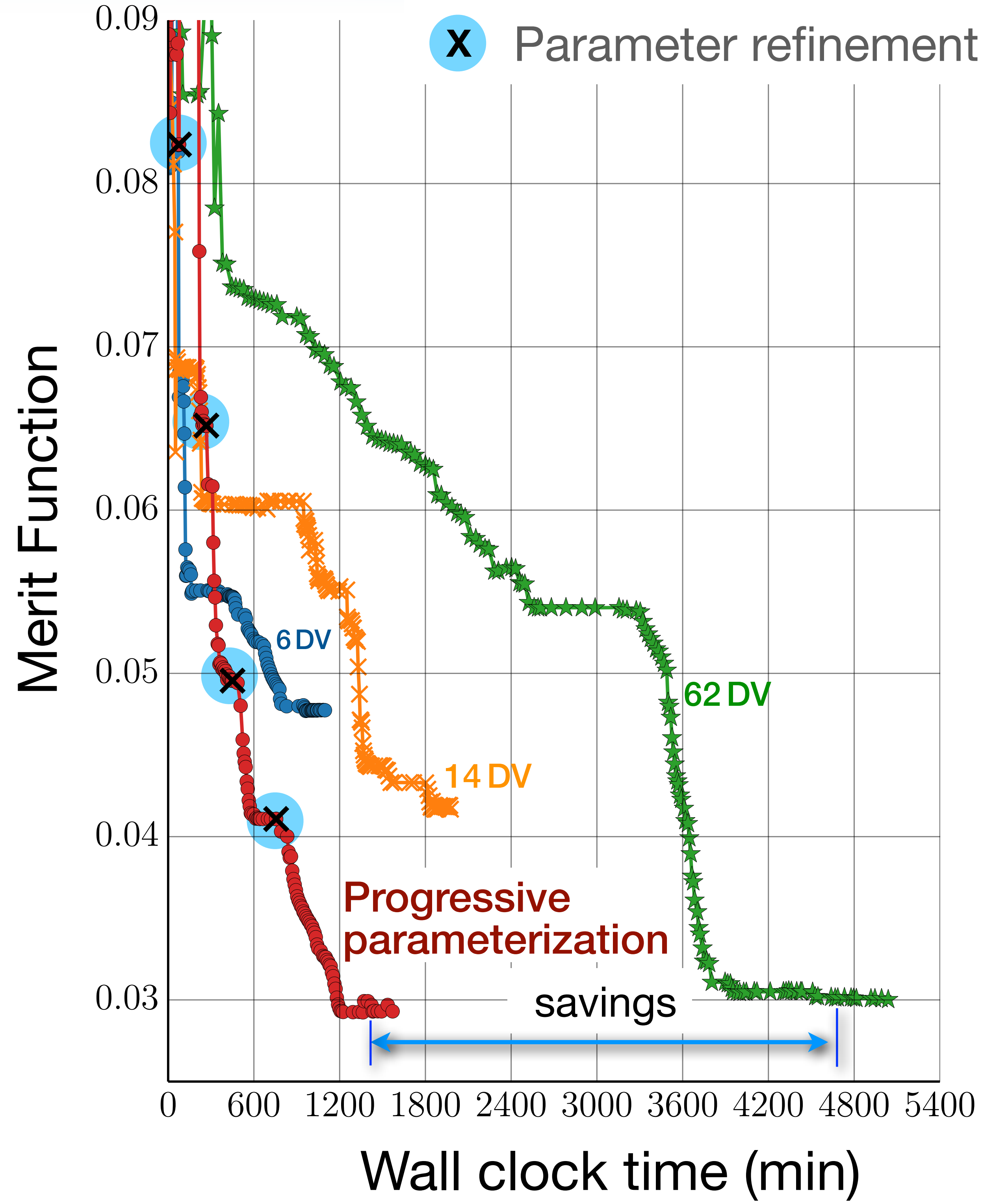

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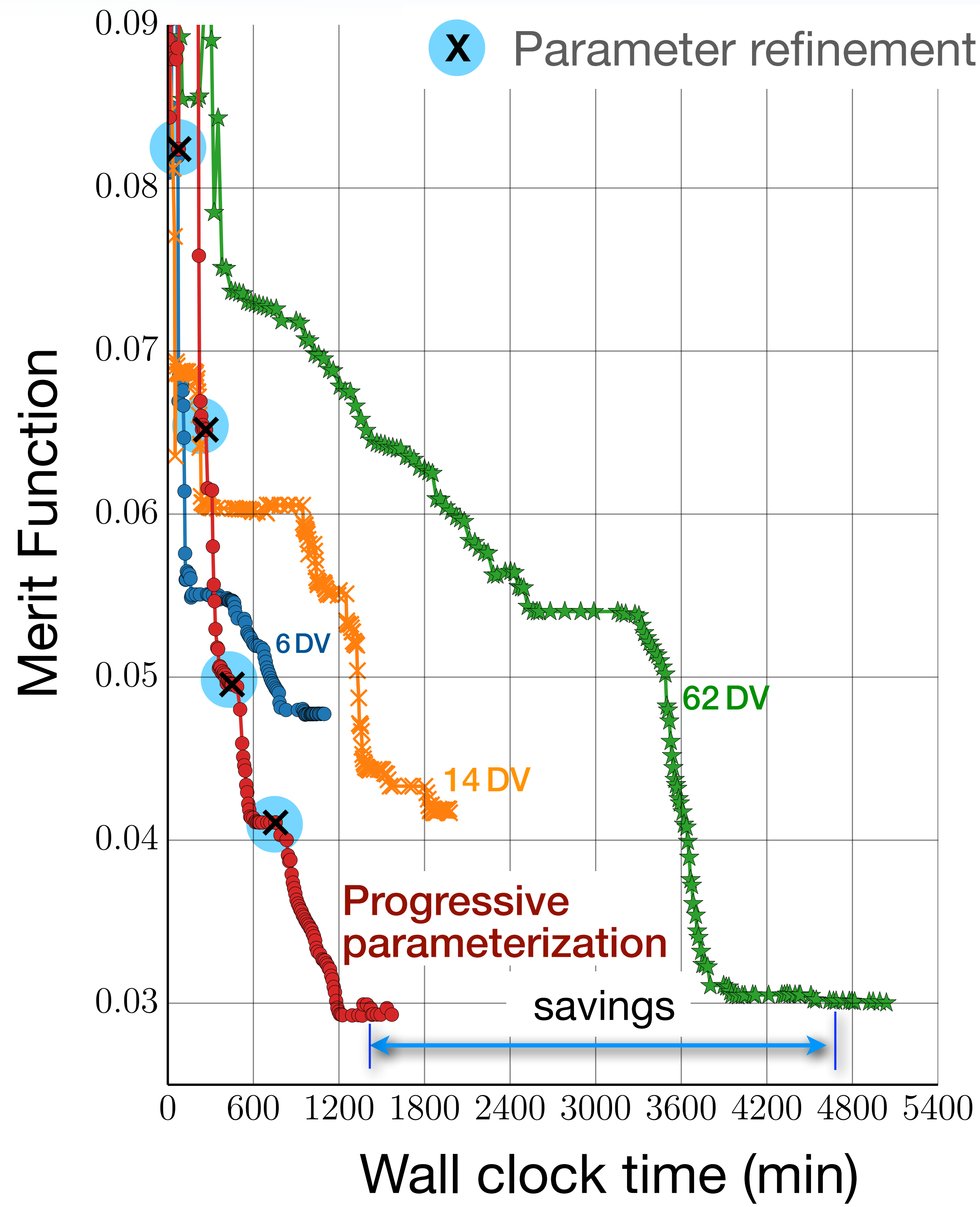
Technical Approach

Progressive Parameterization

- Increase fidelity of control as design progresses
- Fast initial improvement – while still approaching continuous optimum
- Robustness of savings are dependent upon the *trigger* that initiates refinement (*pacing*)
- Details of *slope-based trigger* are in AIAA 2015-0398



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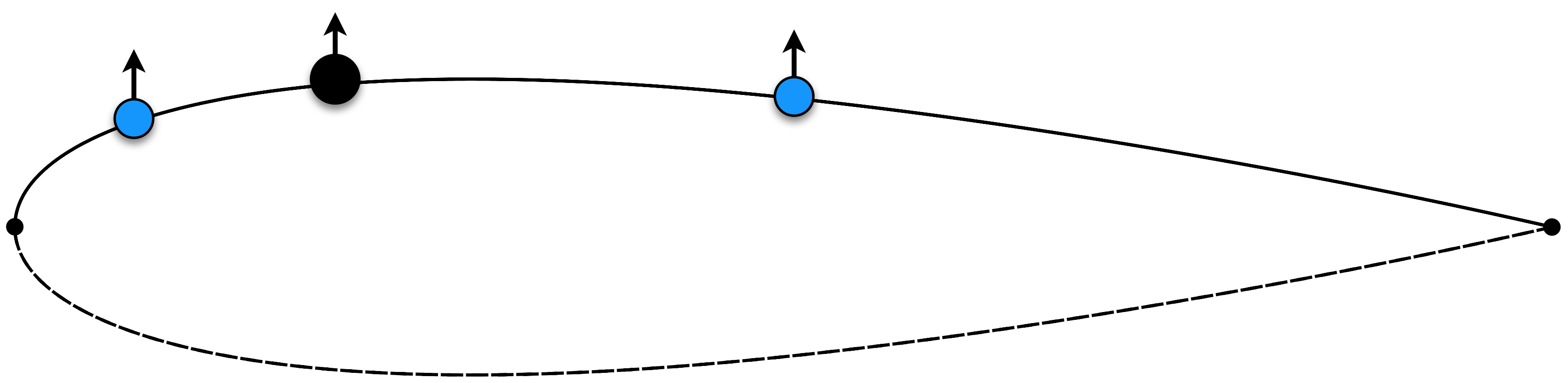
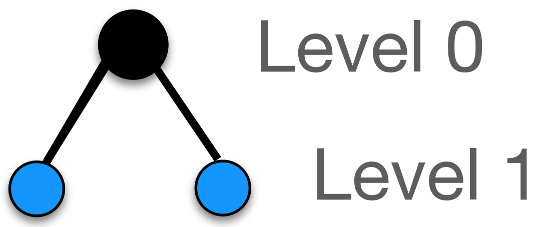
Technical Approach

Parameterization Mechanics

- Lots of options for how to refine the parameterization...
- Currently, each class of parameters is viewed as a **binary tree**





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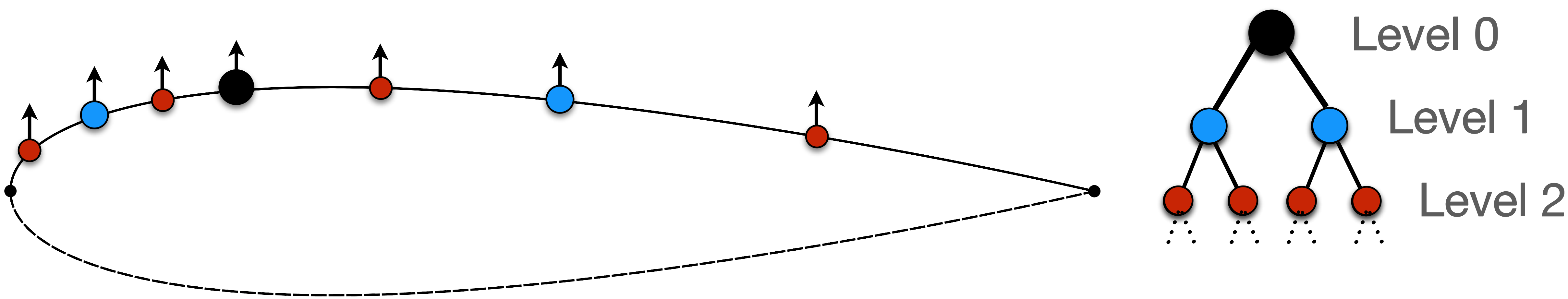

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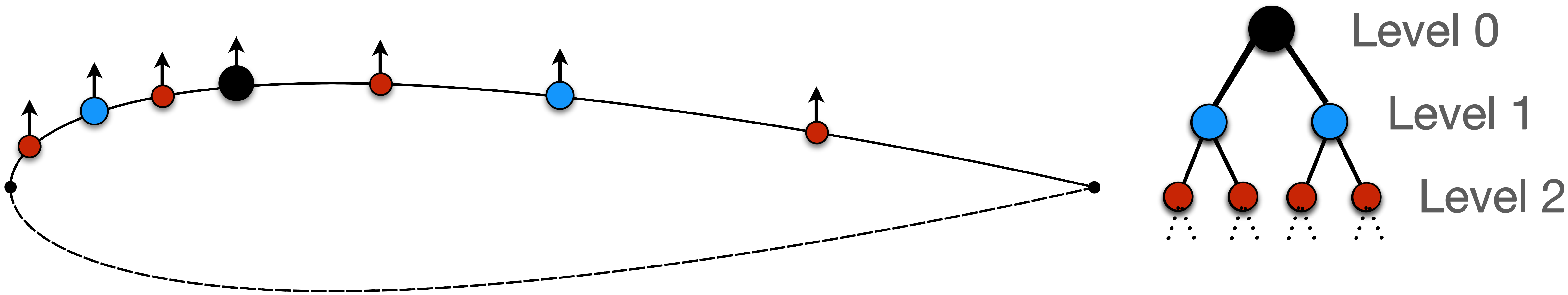

Easily extended to many classes of parameters

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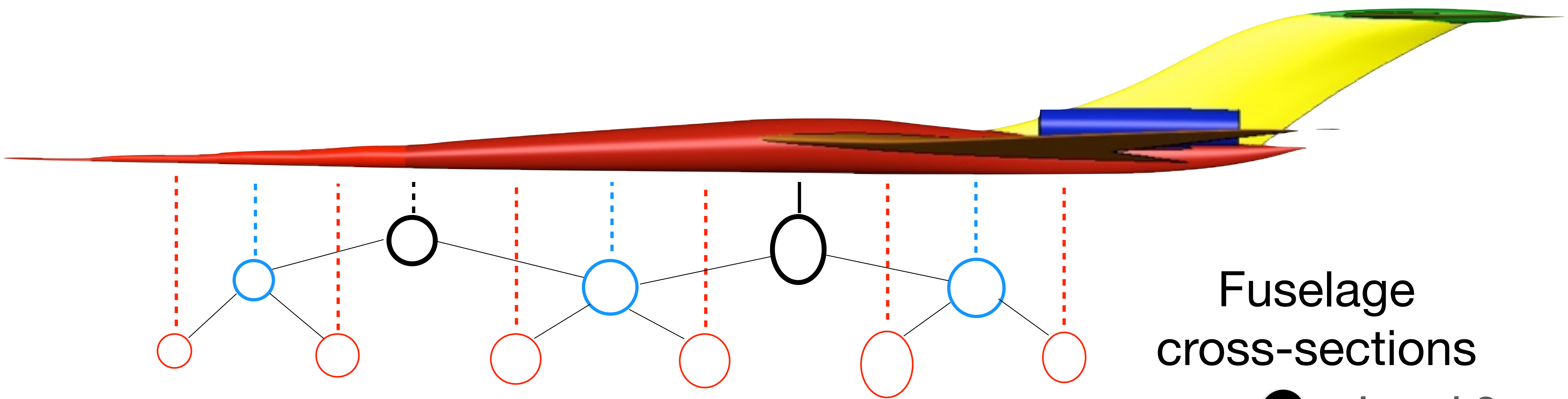

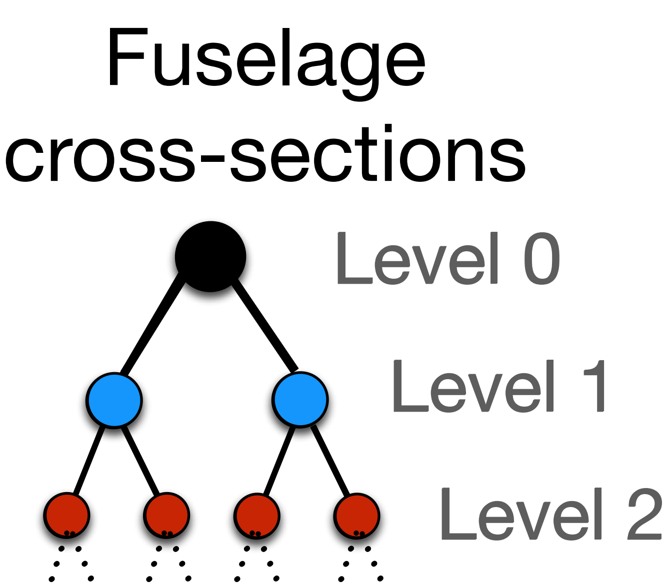

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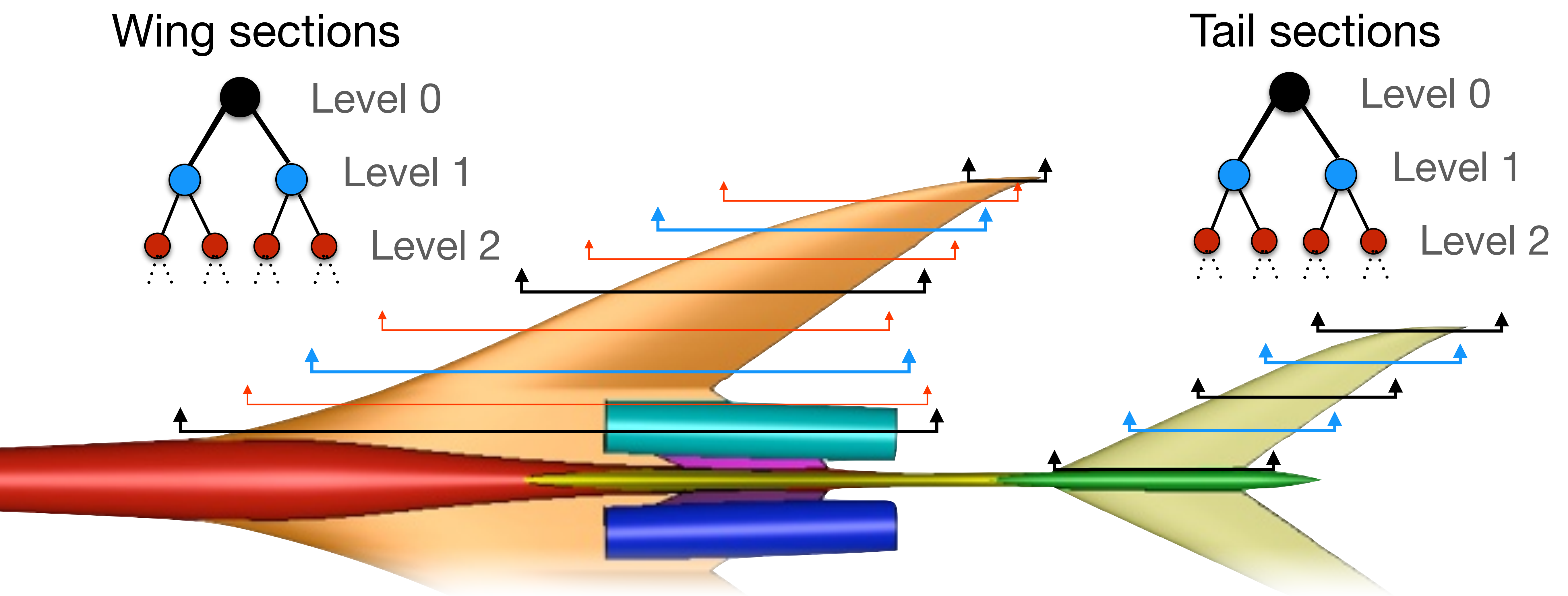


Technical Approach

✓ Parametric control of Discrete Geometry

✓ Progressive shape parameterization

Efficiently approach optima of continuous problem

- Automatic adaptive shape control

  Automatically increase shape control – reduce dependence on designer skill

  Adjoint-based sensitivity information to selectively target specific regions

  Accelerate design

Technical Approach

Automatic adaptive shape control

✓ **How** to introduce new parameters?

Constraint-based deformation + forest of binary trees

✓ **When** to trigger refinement?

Pacing controlled via a slope-based trigger

- **Where** to introduce additional shape control?

  Simple progressive refinement is essentially "uniform refinement"

  Adaptive refinement seeks to add only the most important candidates

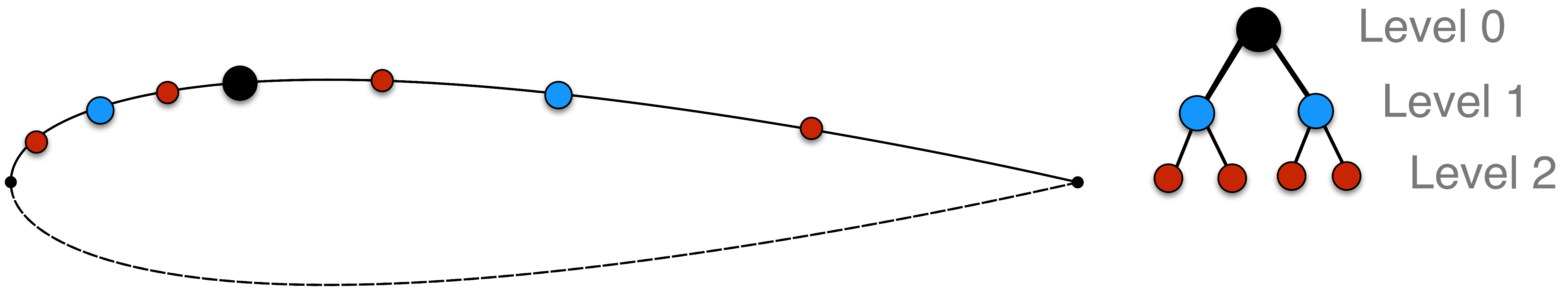
  Mechanics look like adaptive h-refinement in mesh generation

Technical Approach

Automatic adaptive shape control

- Candidate shape parameters

Goal is to increase fidelity of shape control only in locations that have the most potential for improving the objective function



Existing set of shape control parameters

Technical Approach

Automatic adaptive shape control

- Candidate shape parameters

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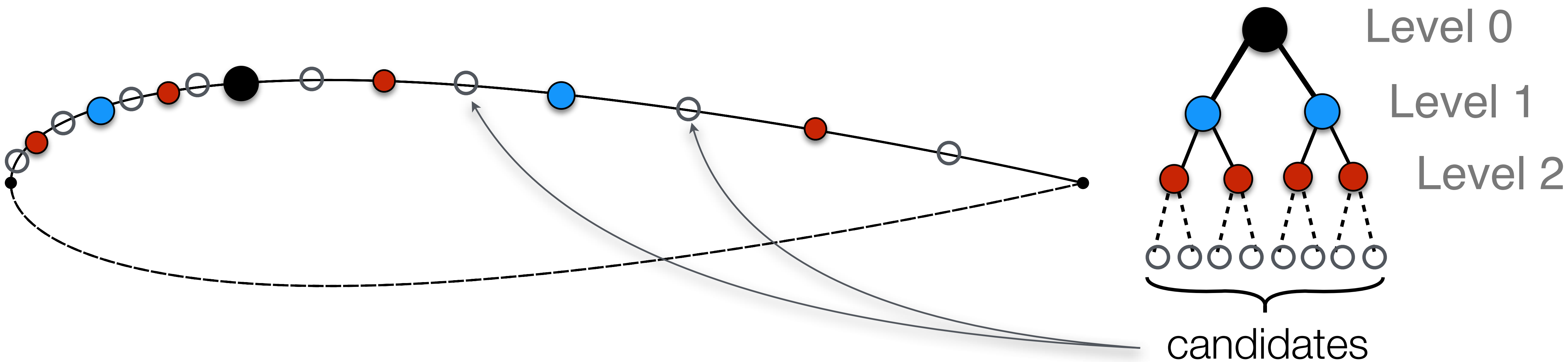
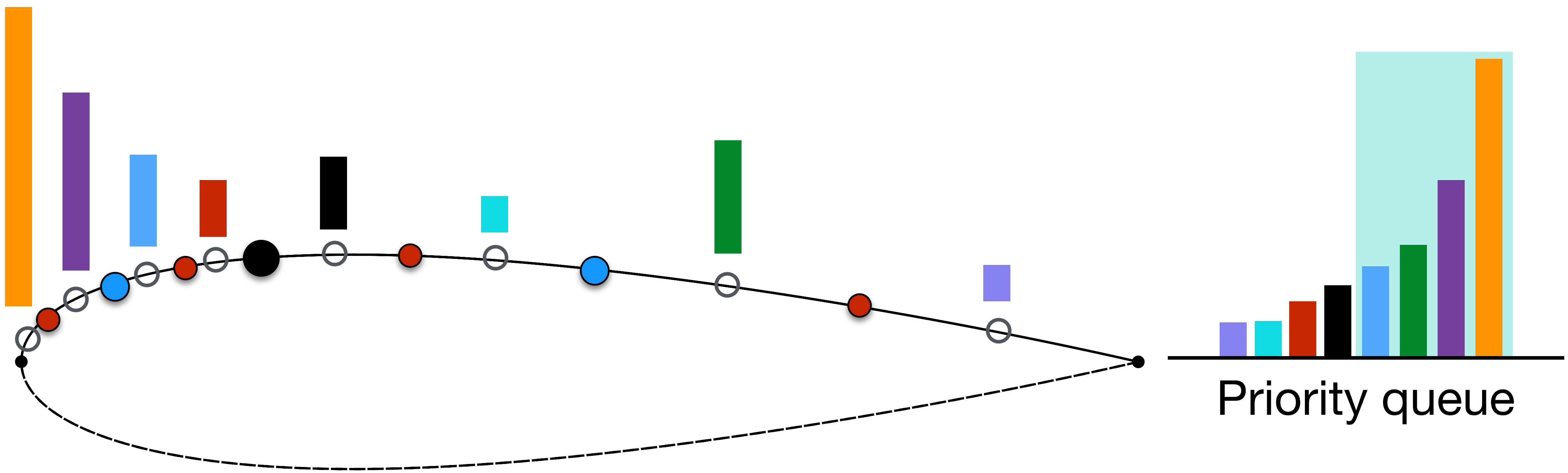


1. Modeler provides a list of possible candidates for refinement

Technical Approach

Automatic adaptive shape control

- **Rank candidates** by "effectiveness indicator"



1. Modeler provides a list of possible candidates for refinement
2. Rank candidates by predicted effectiveness

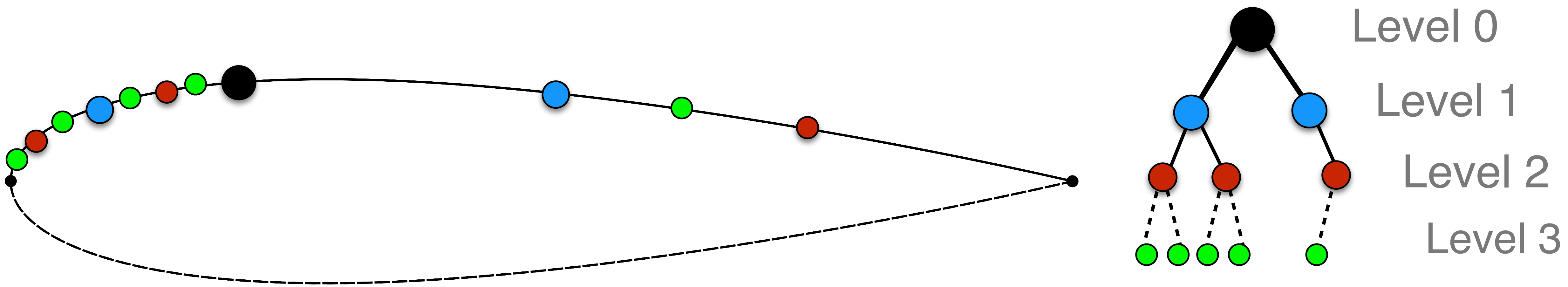
   "effectiveness indicator" similar to "error indicator" in mesh adaptation

Technical Approach

Automatic adaptive shape control

- Add the most important candidates

  Avoid adding flexibility where it won't improve the design

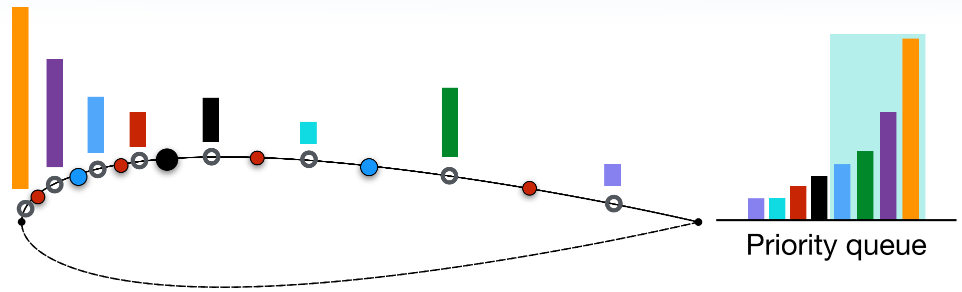


1. Modeler provides a list of possible candidates for refinement
2. Rank candidates by predicted effectiveness
3. Select the most important candidates from priority queue for addition

   Automatically controls the ***distribution of shape control*** *on the surface*

Technical Approach

Adjoint-based “effectiveness indicator”



- Already solving the adjoint for the design sensitivities

$$\left[\frac{\partial \mathbf{R}}{\partial \mathbf{Q}}\right]^{\mathrm{T}} \psi = \frac{\partial \mathcal{J}}{\partial \mathbf{Q}}^{\mathrm{T}} \qquad \text{(adjoint eq.)}$$

- Cost of gradient w/r/t each design variable, X, is roughly one flow residual

$$\frac{\mathrm{d}\mathcal{J}}{\mathrm{d}X} = \frac{\partial \mathcal{J}}{\partial X} + \frac{\partial \mathcal{J}}{\partial \mathbf{M}}\frac{\partial \mathbf{M}}{\partial \mathbf{T}}\frac{\partial \mathbf{T}}{\partial X} - \psi^{\mathrm{T}}\left(\frac{\partial \mathbf{R}}{\partial X} + \frac{\partial \mathbf{R}}{\partial \mathbf{M}}\frac{\partial \mathbf{M}}{\partial \mathbf{T}}\frac{\partial \mathbf{T}}{\partial X}\right)$$

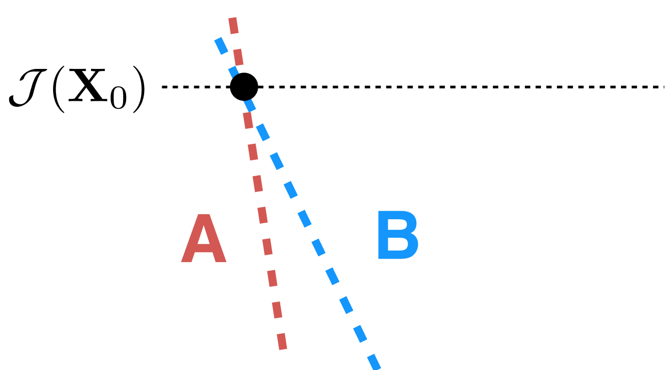
- Treat the all the candidate DVs as design variables $\mathrm{d}\mathcal{J}/\mathrm{d}X_C$ predicts precisely the sensitivity of the design objective to each candidate

For the cost of a few additional gradient evaluations, the adjoint offers an effectiveness indicator for each candidate DV

Technical Approach

Adjoint-based “effectiveness indicator”

- Gradients are based on local linearization about current state

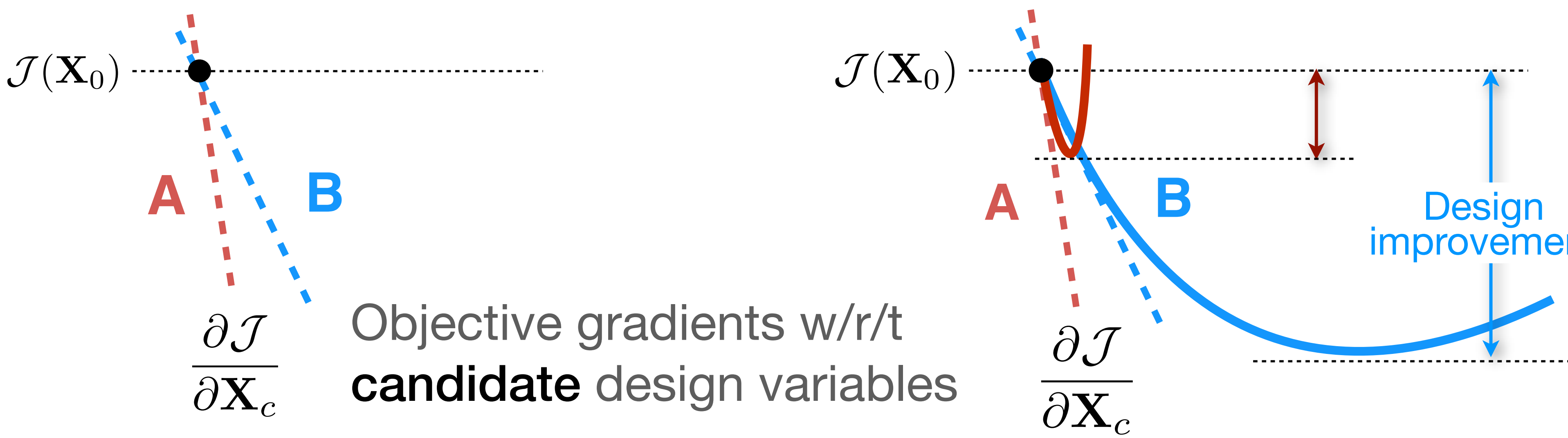


$$\frac{\partial \mathcal{J}}{\partial \mathbf{X}_c}$$ Objective gradients w/r/t **candidate** design variables

Technical Approach

Adjoint-based "effectiveness indicator"

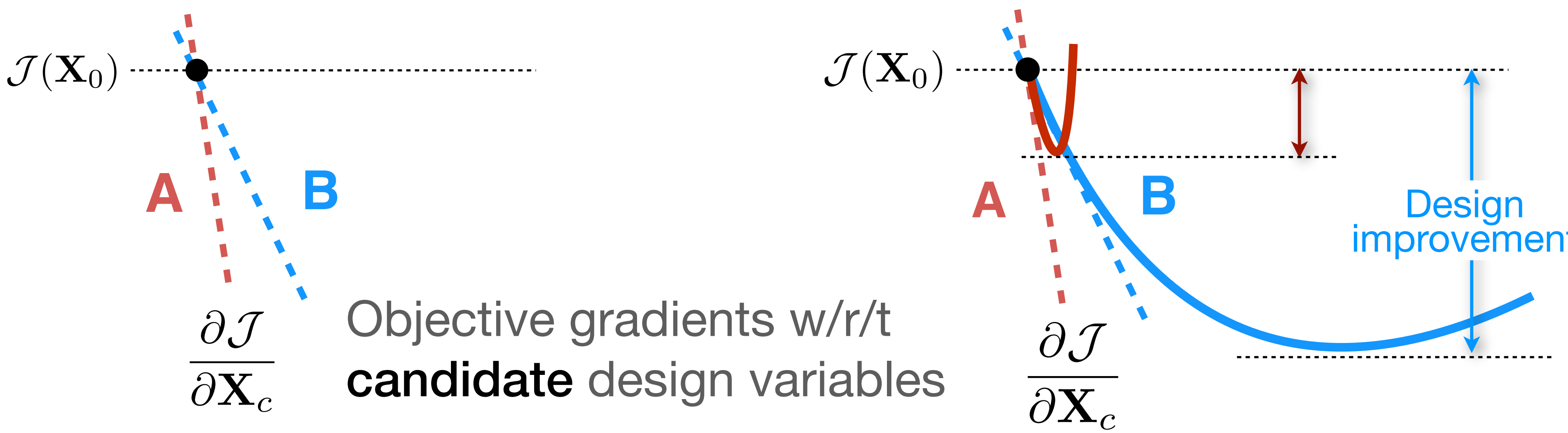
- Gradients are based on local linearization about current state
- Not always good predictors of design improvement...



Technical Approach

Adjoint-based “effectiveness indicator”

- Gradients are based on local linearization about current state
- Not always good predictors of design improvement...



- Currently investigating the use of Hessian information to improve effectiveness indicator
- Considering approximate Hessians, or even just the trace of the Hessian for scaling the gradient info.
- See details in *AIAA 2015-0398* “Adaptive shape control for aerodynamic design”, Jan. 2015.

Technical Approach

Automatic adaptive shape control

✓ How to introduce new parameters?

Constraint-based deformation + forest of binary trees

✓ When to trigger refinement?

Pacing controlled via a slope-based trigger

✓ Where to introduce additional shape control?

– Use adjoint sensitivities to compute "effectiveness indicator" for candidates based on h-refinement of parameterization

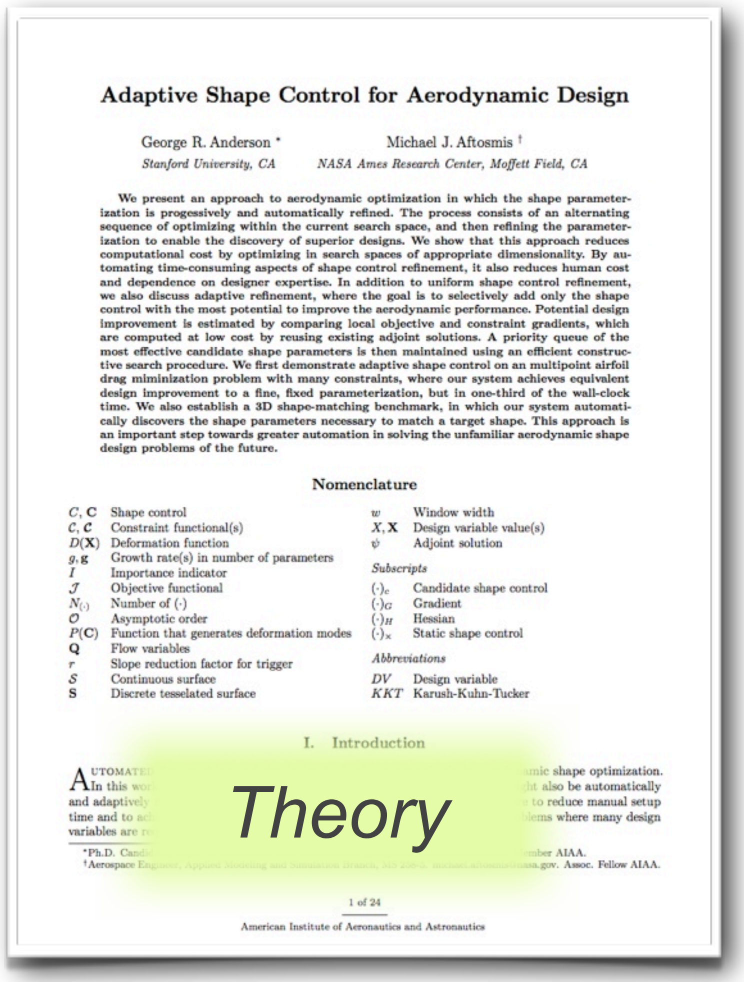
– Use of reduced Hessian information still under investigation

Results

- Detailed results presented in recent publications

Jan 2015, AIAA SciTech meeting

AIAA 2015-0398 "Adaptive shape control for aerodynamic design"



Adaptive Shape Control for Aerodynamic Design

George R. Anderson *
Stanford University, CA

Michael J. Aftosmis †
NASA Ames Research Center, Moffett Field, CA

We present an approach to aerodynamic optimization in which the shape parameterization is progessively and automatically refined. The process consists of an alternating sequence of optimizing within the current search space, and then refining the parameterization to enable the discovery of superior designs. We show that this approach reduces computational cost by optimizing in search spaces of appropriate dimensionality. By automating time-consuming aspects of shape control refinement, it also reduces human cost and dependence on designer expertise. In addition to uniform shape control refinement, we also discuss adaptive refinement, where the goal is to selectively add only the shape control with the most potential to improve the aerodynamic performance. Potential design improvement is estimated by comparing local objective and constraint gradients, which are computed at low cost by reusing existing adjoint solutions. A priority queue of the most effective candidate shape parameters is then maintained using an efficient constructive search procedure. We first demonstrate adaptive shape control on an multipoint airfoil drag miminization problem with many constraints, where our system achieves equivalent design improvement to a fine, fixed parameterization, but in one-third of the wall-clock time. We also establish a 3D shape-matching benchmark, in which our system automatically discovers the shape parameters necessary to match a target shape. This approach is an important step towards greater automation in solving the unfamiliar aerodynamic shape design problems of the future.

Nomenclature

$C, \mathbf{C}$	Shape control	w	Window width
$\mathcal{C}, \boldsymbol{\mathcal{C}}$	Constraint functional(s)	$X, \mathbf{X}$	Design variable value(s)
$D(\mathbf{X})$	Deformation function	ψ	Adjoint solution

I. Introduction

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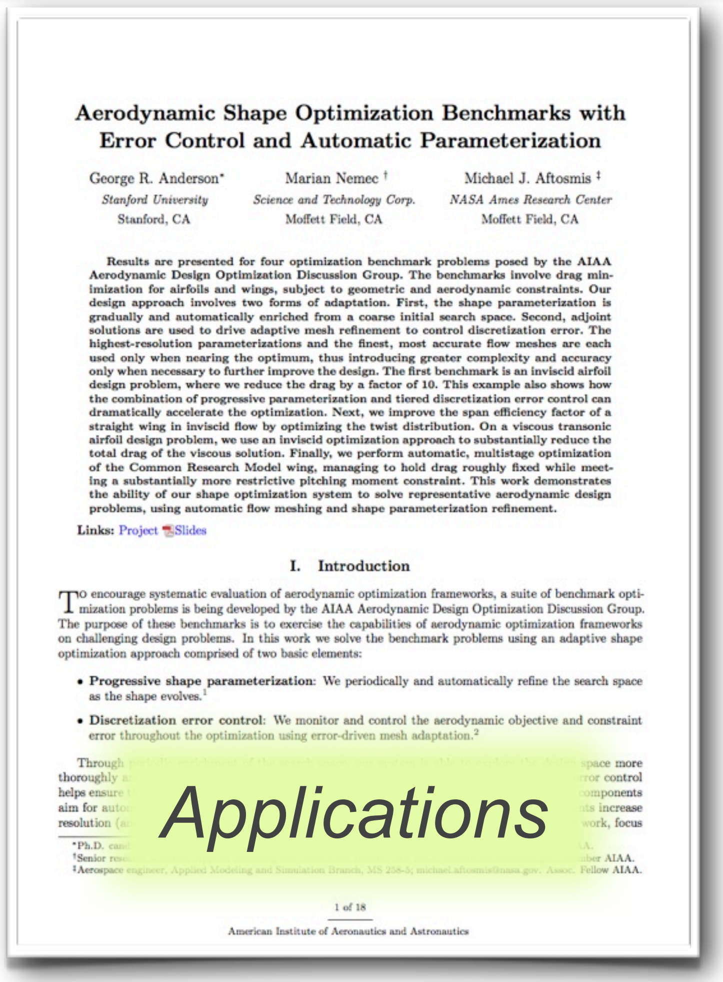
American Institute of Aeronautics and Astronautics

AIAA 2015-1719 "Aerodynamic shape optimization benchmarks with error control and automatic parameterization"



Aerodynamic Shape Optimization Benchmarks with Error Control and Automatic Parameterization

George R. Anderson*
Stanford University
Stanford, CA

Marian Nemec †
Science and Technology Corp.
Moffett Field, CA

Michael J. Aftosmis ‡
NASA Ames Research Center
Moffett Field, CA

Results are presented for four optimization benchmark problems posed by the AIAA Aerodynamic Design Optimization Discussion Group. The benchmarks involve drag minimization for airfoils and wings, subject to geometric and aerodynamic constraints. Our design approach involves two forms of adaptation. First, the shape parameterization is gradually and automatically enriched from a coarse initial search space. Second, adjoint solutions are used to drive adaptive mesh refinement to control discretization error. The highest-resolution parameterizations and the finest, most accurate flow meshes are each used only when nearing the optimum, thus introducing greater complexity and accuracy only when necessary to further improve the design. The first benchmark is an inviscid airfoil design problem, where we reduce the drag by a factor of 10. This example also shows how the combination of progressive parameterization and tiered discretization error control can dramatically accelerate the optimization. Next, we improve the span efficiency factor of a straight wing in inviscid flow by optimizing the twist distribution. On a viscous transonic airfoil design problem, we use an inviscid optimization approach to substantially reduce the total drag of the viscous solution. Finally, we perform automatic, multistage optimization of the Common Research Model wing, managing to hold drag roughly fixed while meeting a substantially more restrictive pitching moment constraint. This work demonstrates the ability of our shape optimization system to solve representative aerodynamic design problems, using automatic flow meshing and shape parameterization refinement.

Links: Project Slides

I. Introduction

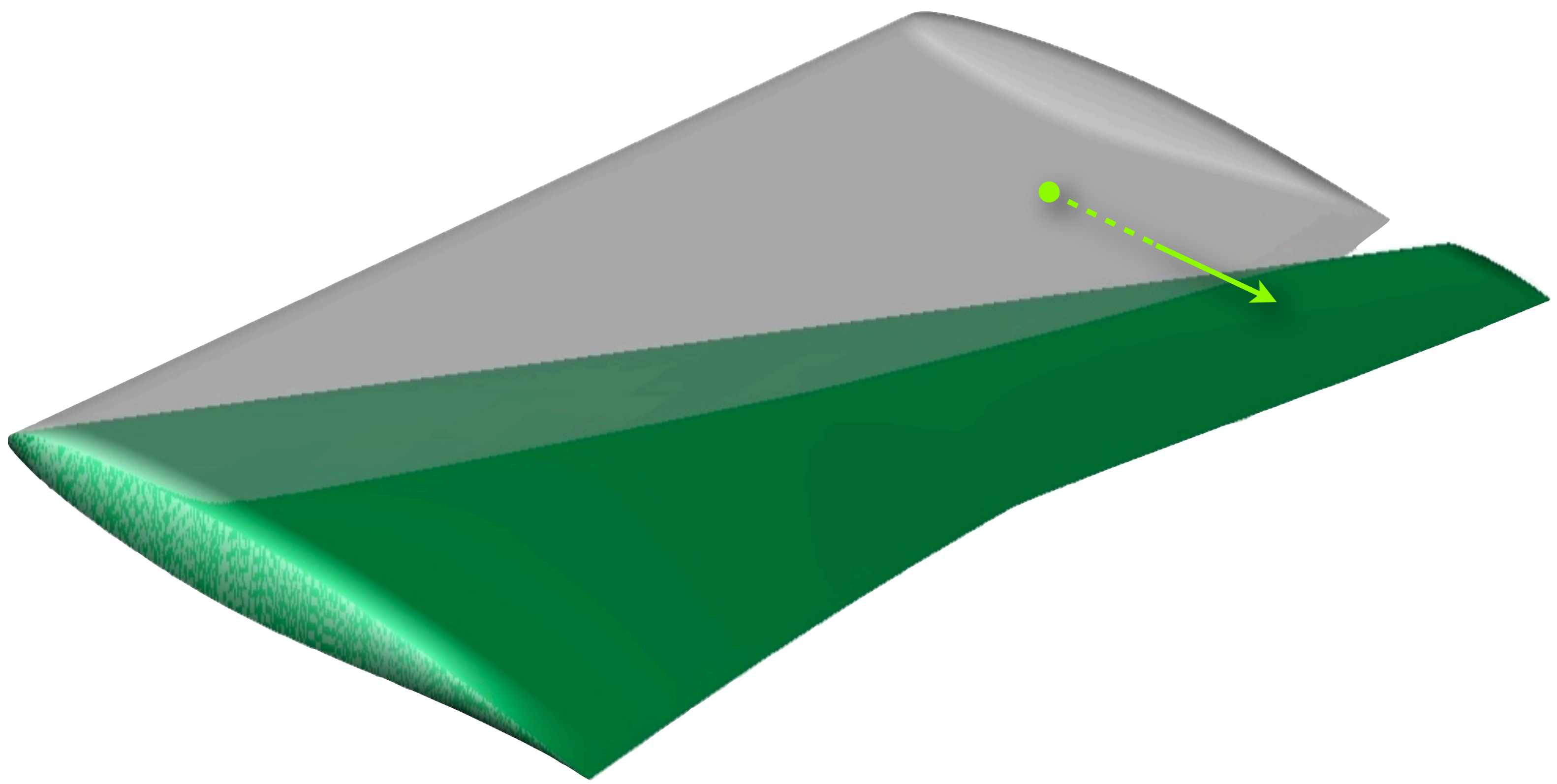
To encourage systematic evaluation of aerodynamic optimization frameworks, a suite of benchmark optimization problems is being developed by the AIAA Aerodynamic Design Optimization Discussion Group.

1 of 18

American Institute of Aeronautics and Astronautics

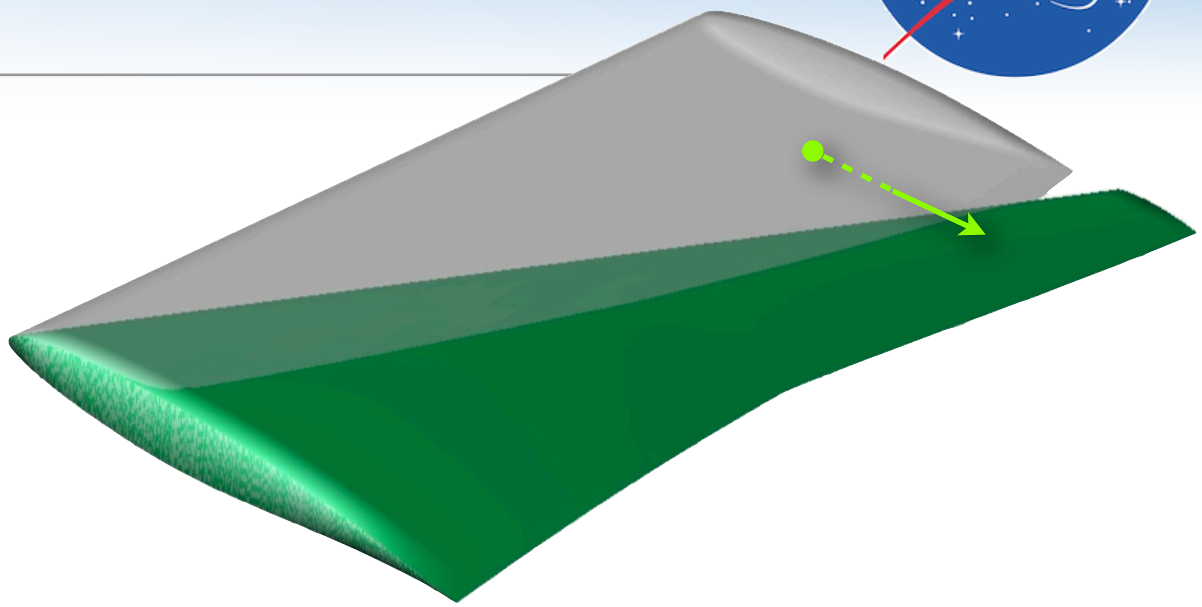
Results

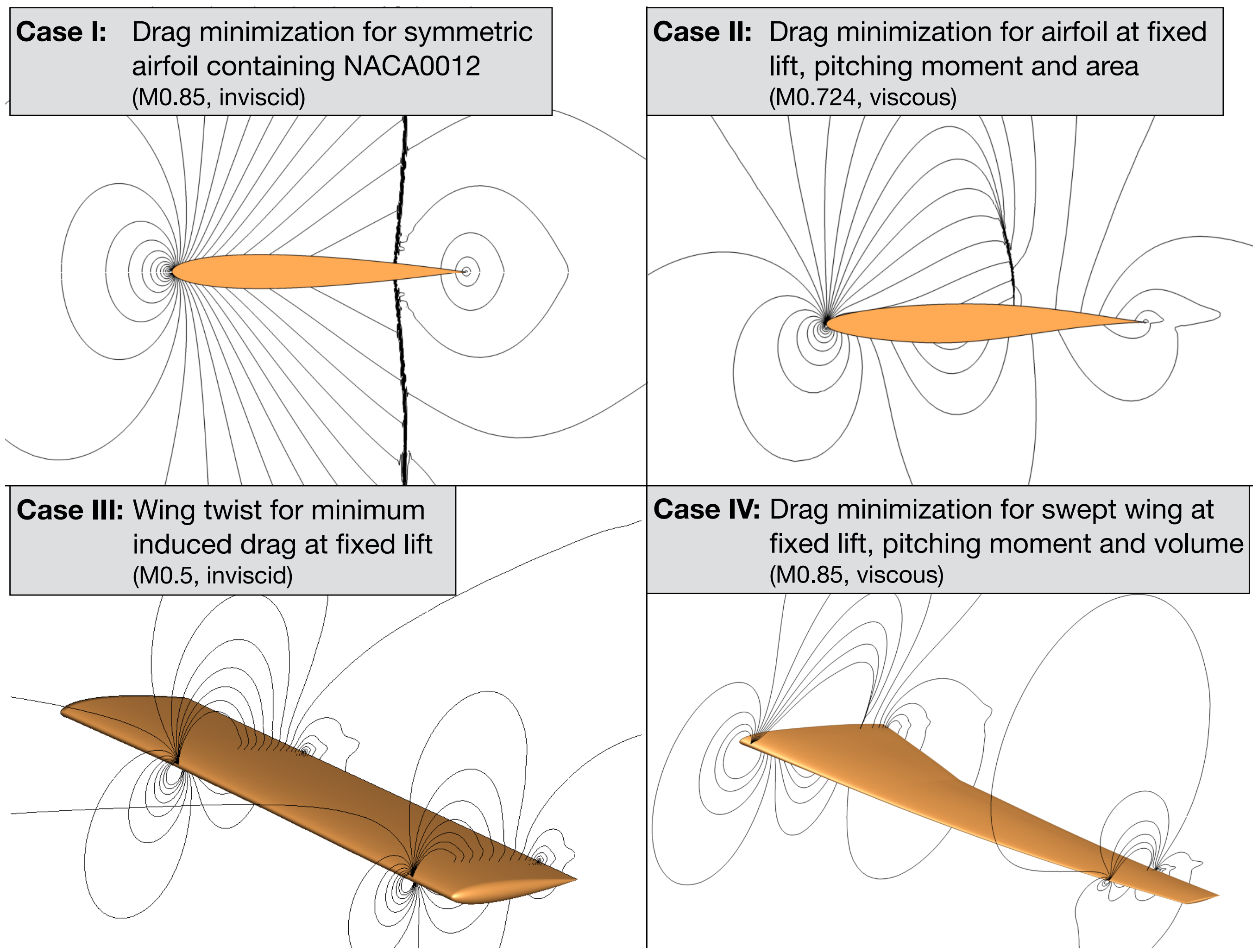
- A few highlights
  - *1. Shape matching for a 3D wing*



Results

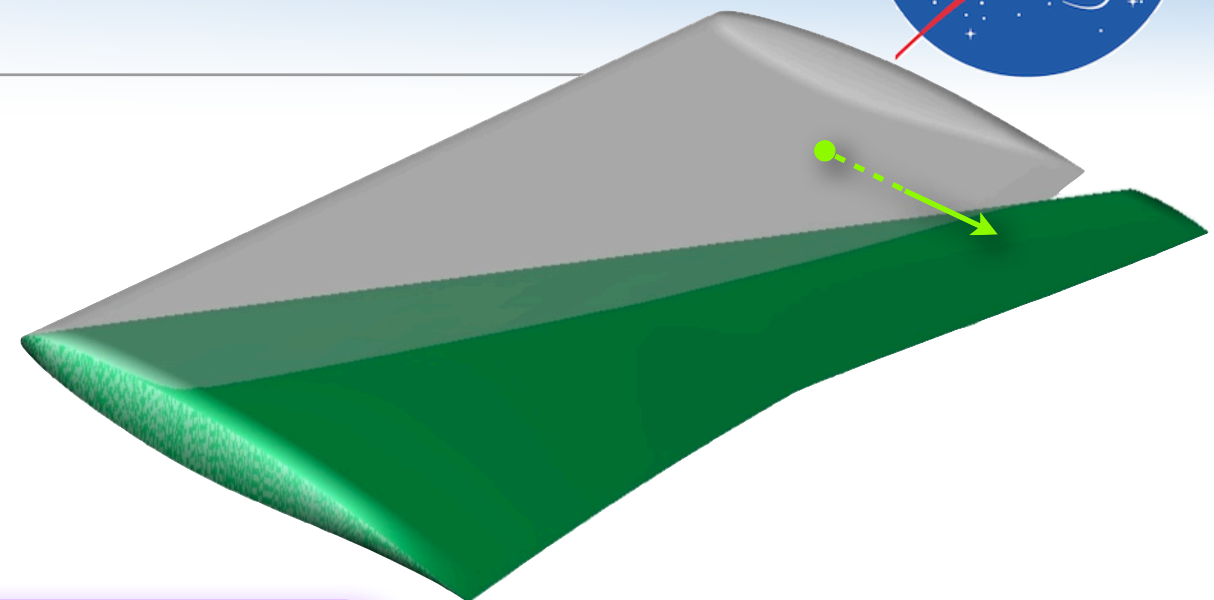
- A few highlights
    1. Shape matching for a 3D wing

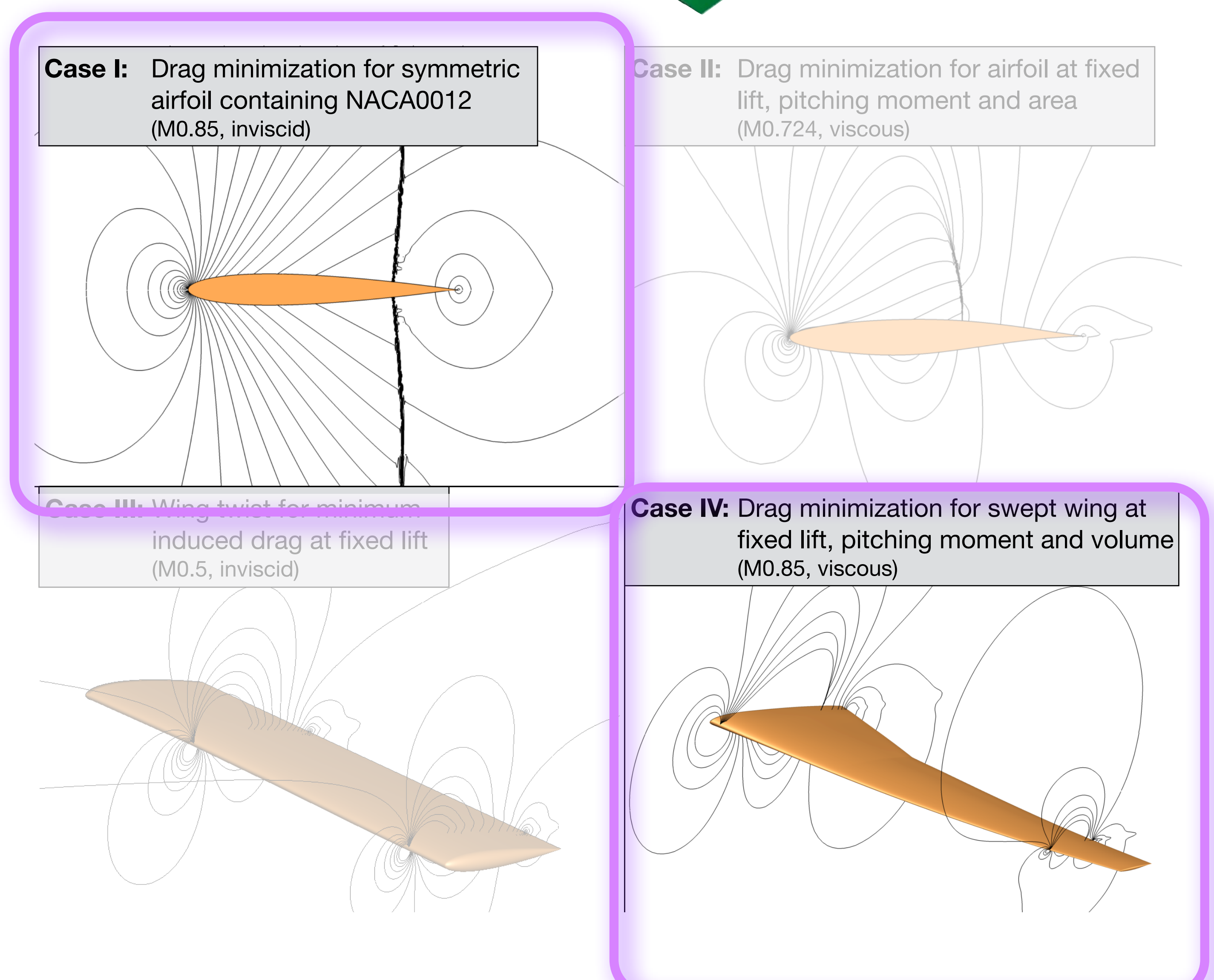




Results

- A few highlights
  1. *Shape matching for a 3D wing*
  2. *Constrained transonic airfoil design*
  3. *Constrained transonic wing design*

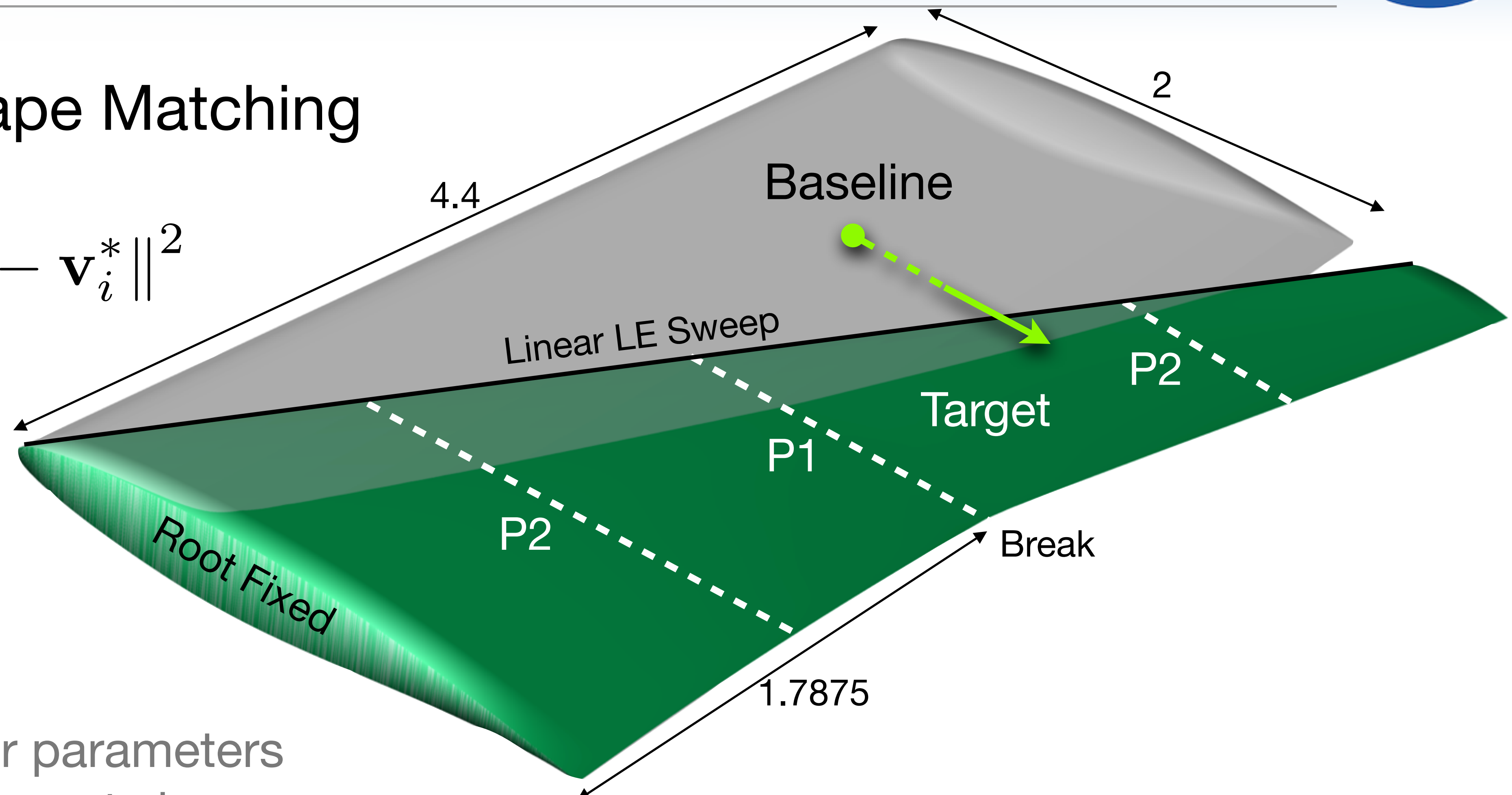




Results

3D Geometric Shape Matching

$$\mathcal{J} = \sum_{i=1}^{N_{verts}} \left\| \mathbf{v}_i - \mathbf{v}_i^* \right\|^2$$

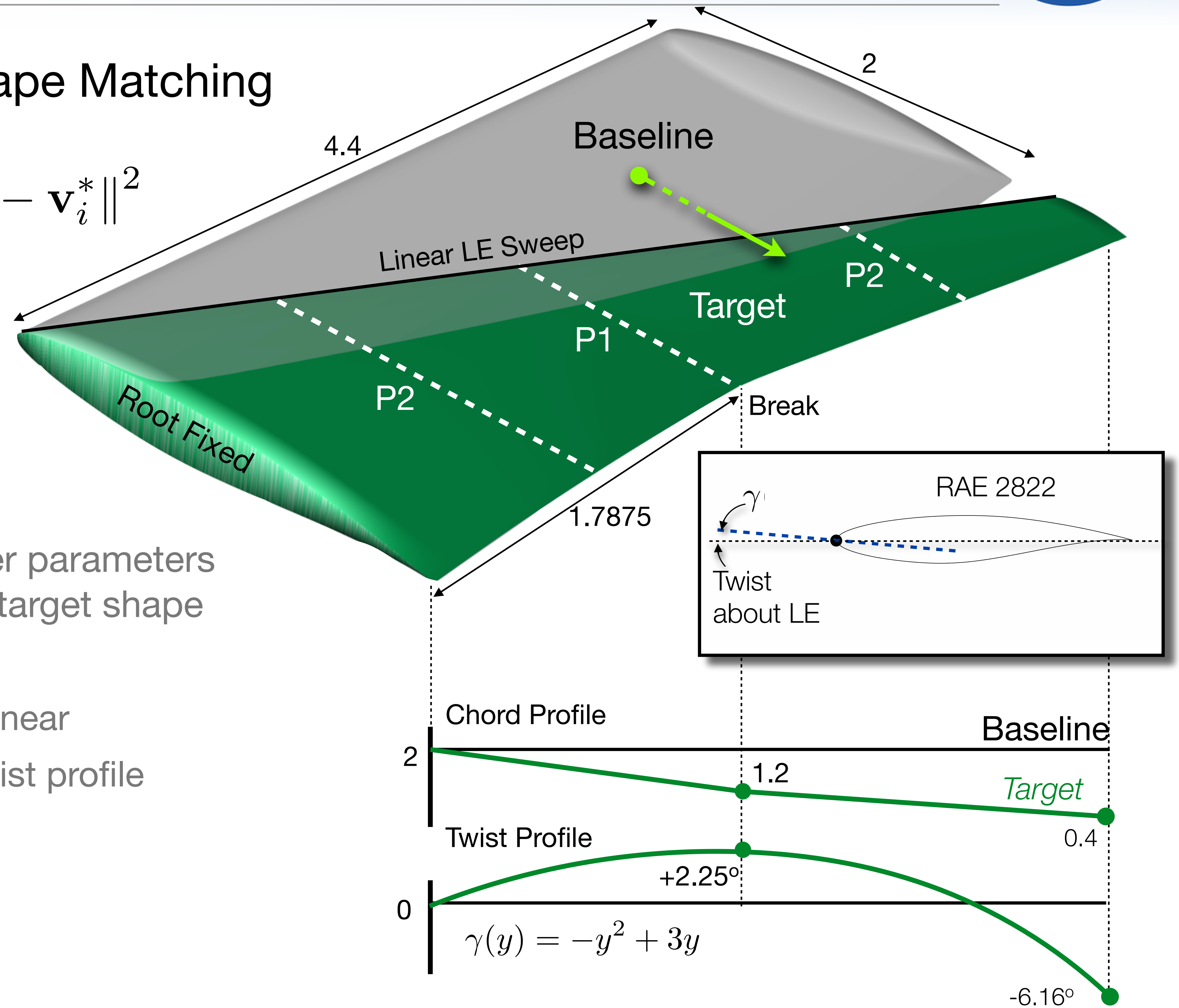


Goal:
Automatically discover parameters needed to match the target shape

Results

3D Geometric Shape Matching

$$\mathcal{J} = \sum_{i=1}^{N_{verts}} \left\| \mathbf{v}_i - \mathbf{v}_i^* \right\|^2$$



Goal:

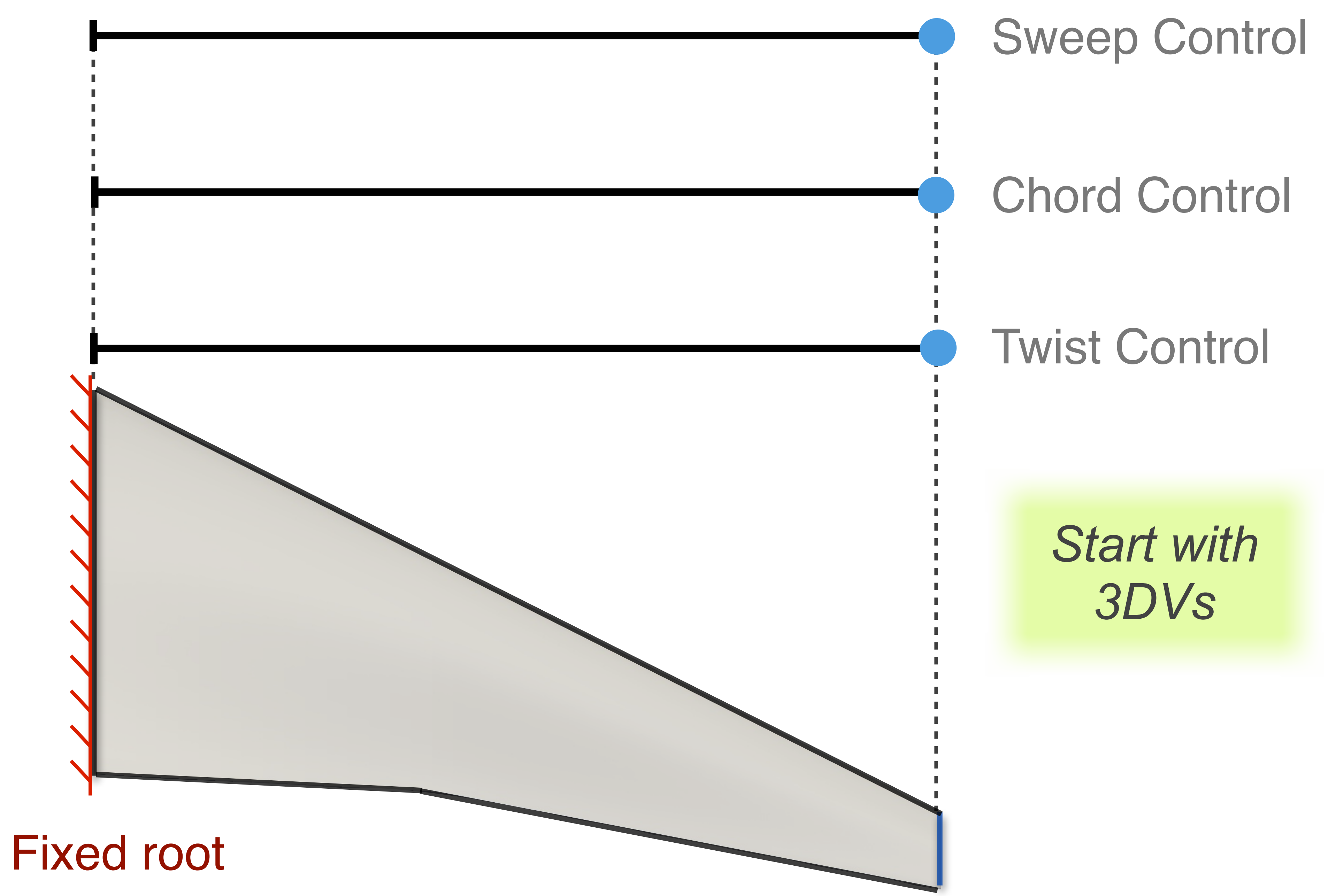
Automatically discover parameters needed to match the target shape

1. Sweep:
2. Chord: Piecewise linear
3. Twist: Quadratic twist profile

Results

3D Geometric Shape Matching

- Initial shape parameterization

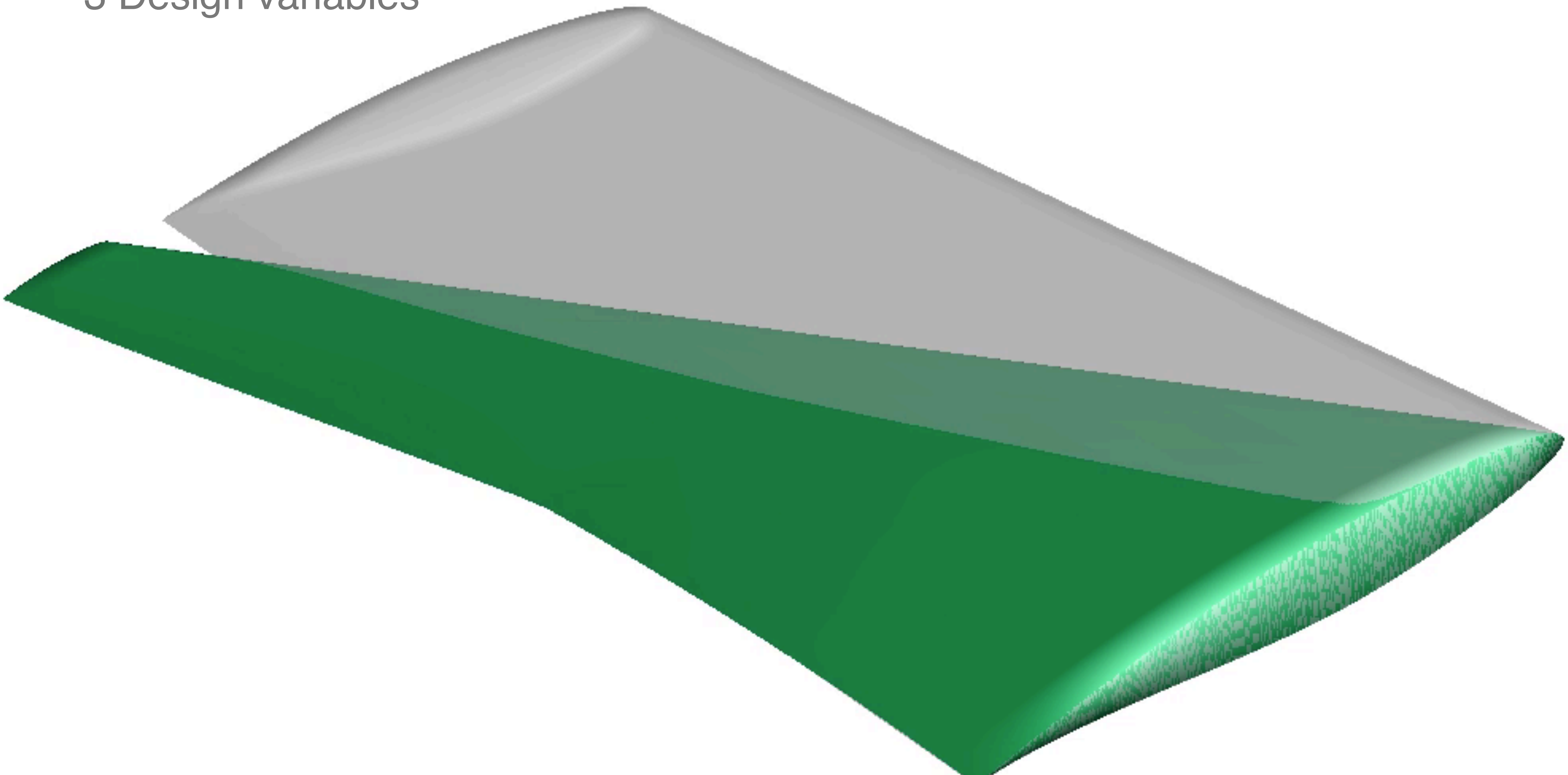


Start with 3DVs

Results

3D Geometric Shape Matching

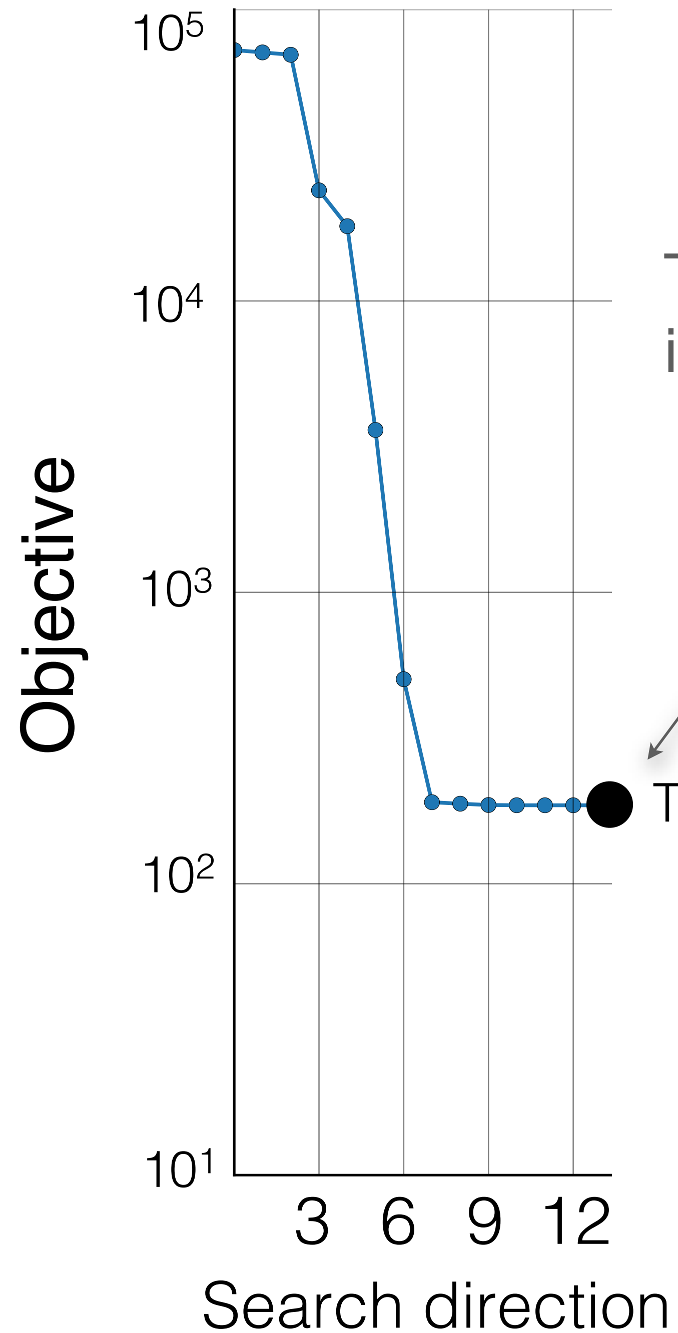
- Initial shape parameterization
- 3 Design variables



Results

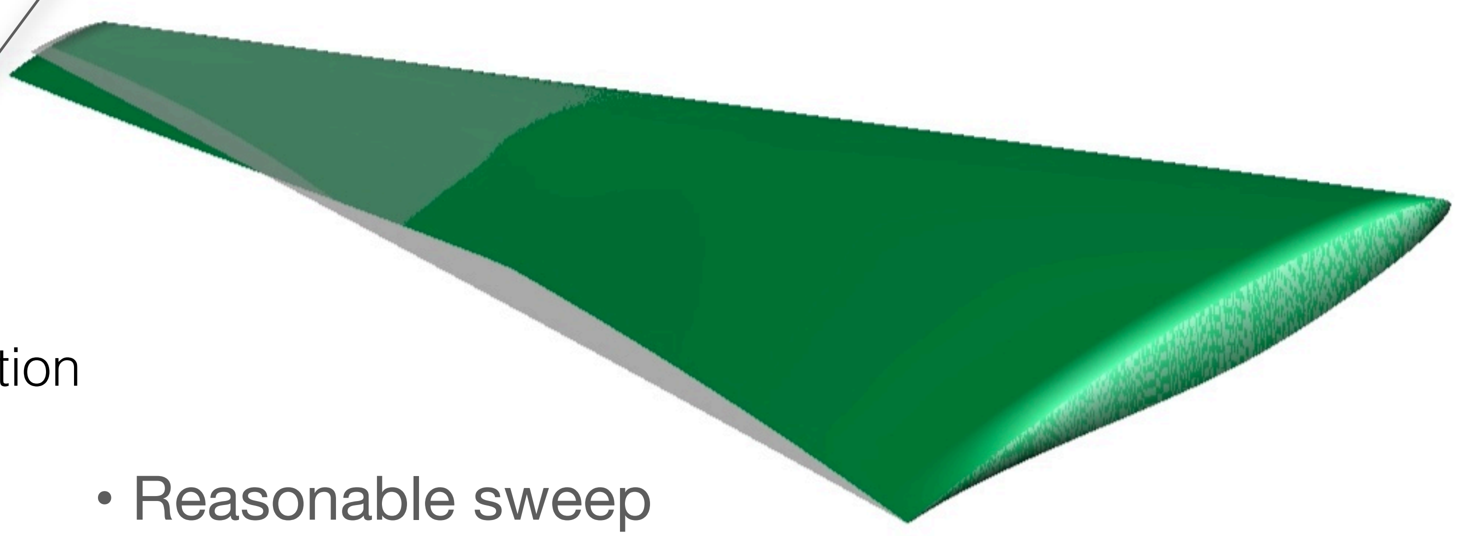
3D Geometric Shape Matching

- Design attempt using initial shape parameterization



$$\mathcal{J} = \sum_{i=1}^{N_{verts}} \left\| \mathbf{v}_i - \mathbf{v}_i^* \right\|^2$$

Target is **unattainable** under the initial 3-DV parameterization.

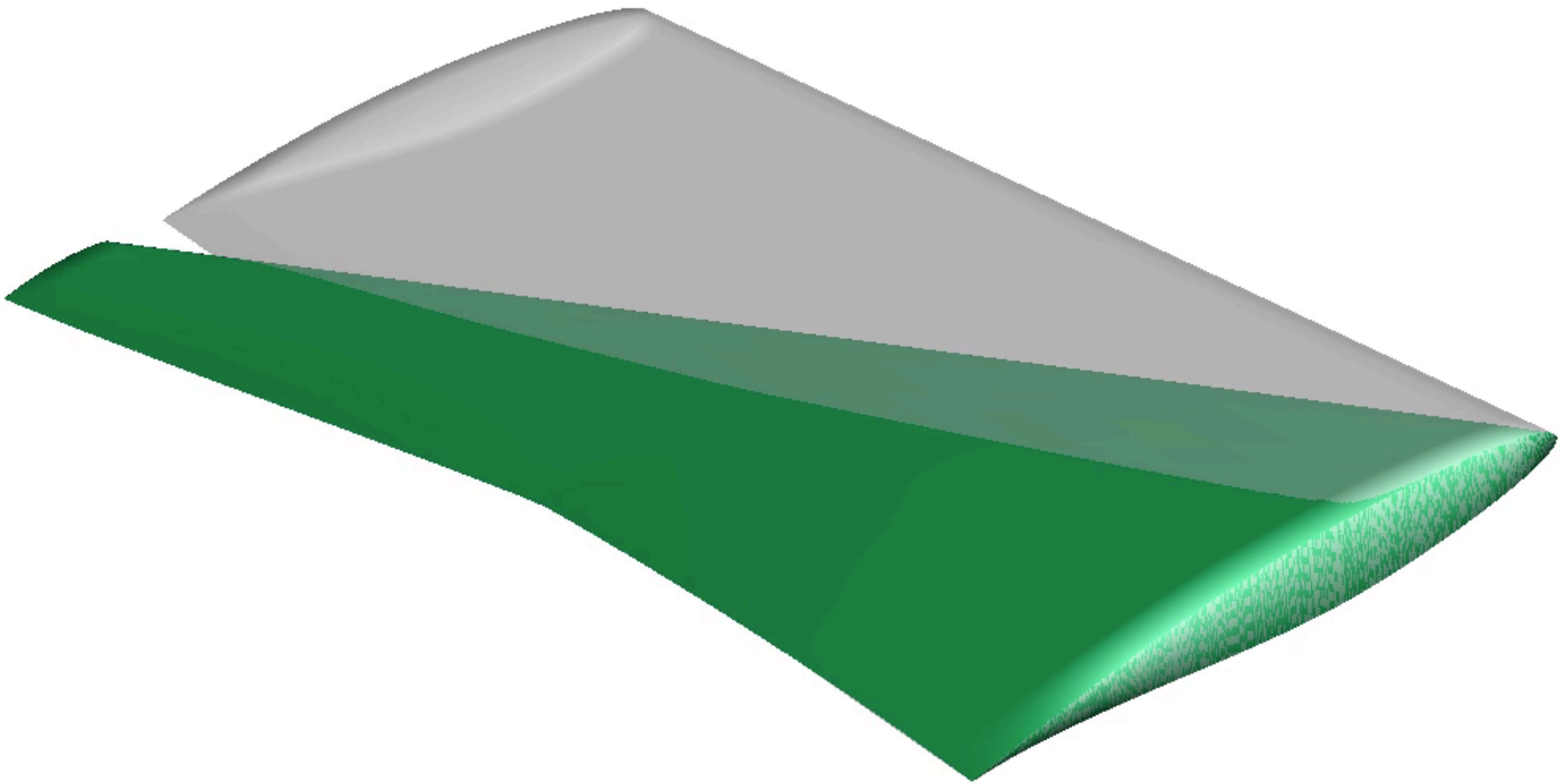


- Reasonable sweep
- Reasonable taper
- No wing break
- Only linear twist

Results

3D Geometric Shape Matching

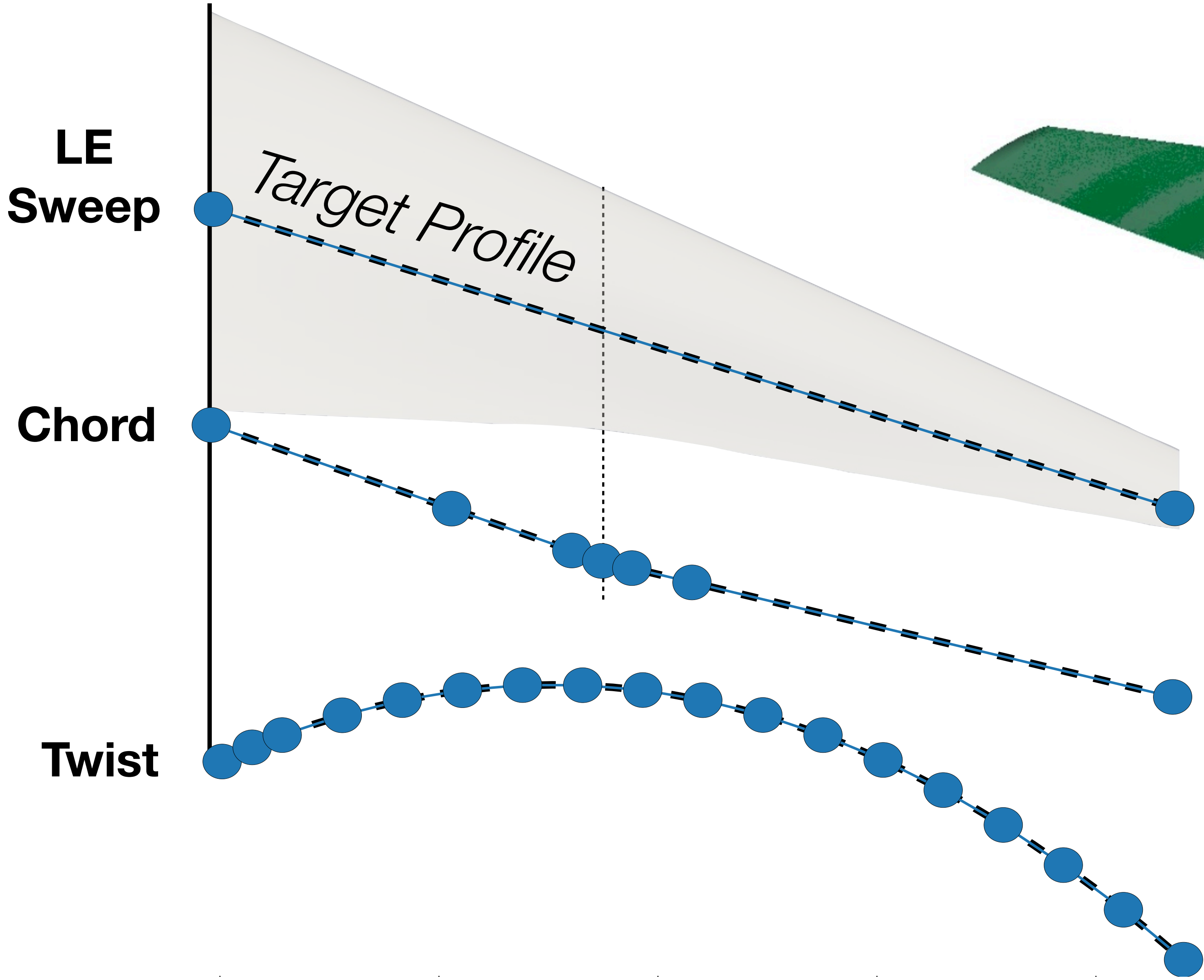
- Adaptive parameterization

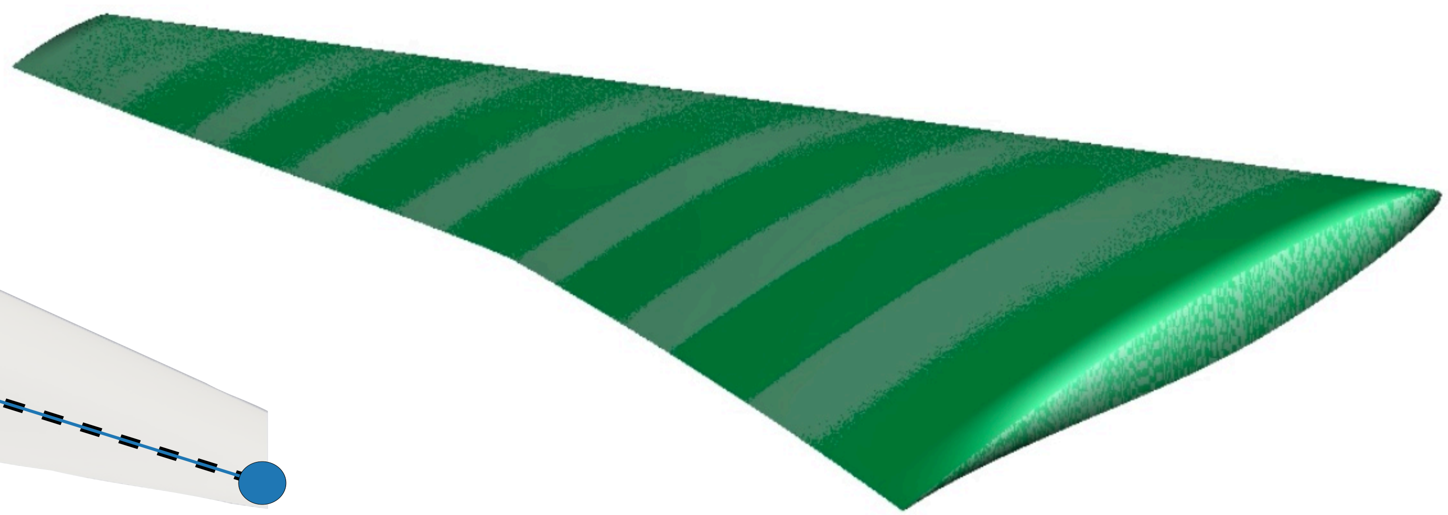


Results

3D Geometric Shape Matching

- Adapt parameterization using Hessian effectiveness indicator



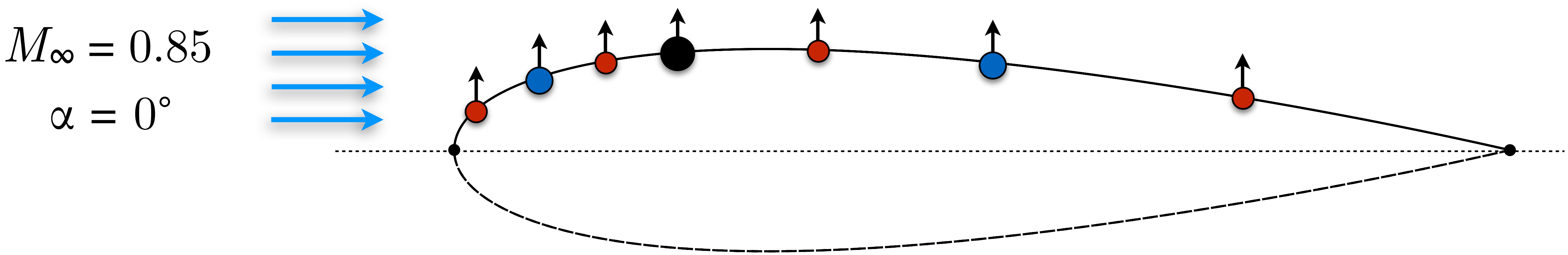


- 24 parameters total
- Excellent match of target profile
- Discovered wing break
- Optimally reducing error in twist
- More details in AIAA 2015-0398

AIAA 2015-0398 “Adaptive shape control for aerodynamic design”

Results

Constrained transonic airfoil design



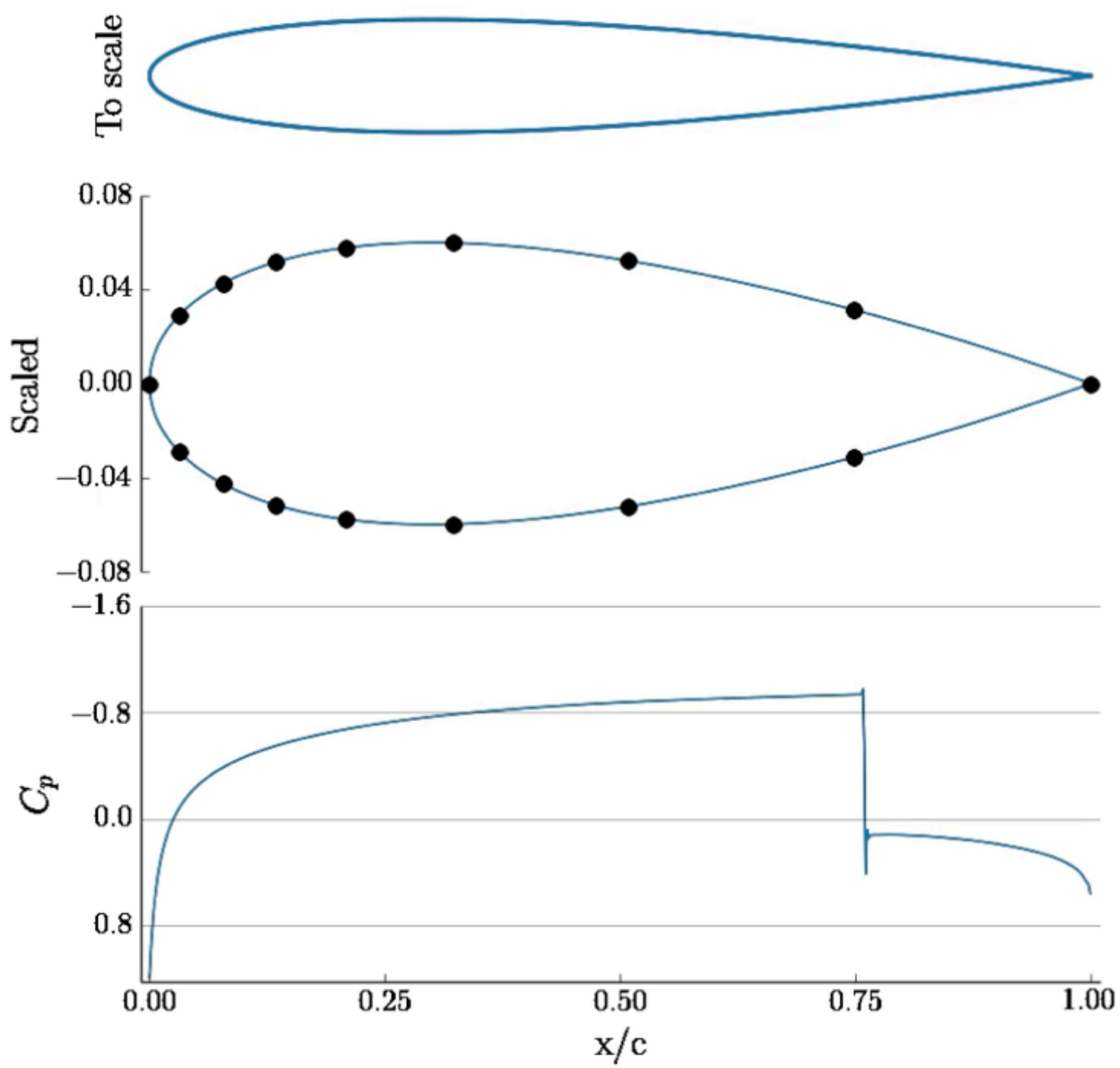
- **SciTech 2015** - Special Session: Aerodynamic Design Benchmarks, Prob. #1.
- **Results Summary:** AIAA 2015-0263 (Méheut et al., 2015)
- **Objective:** Minimize drag at $M_\infty = 0.85$
- **Constraints:** Symmetric, must contain original NACA 0012
- **Parameterization:** Progressive with uniform refinement: 7→15→31→63 DVs

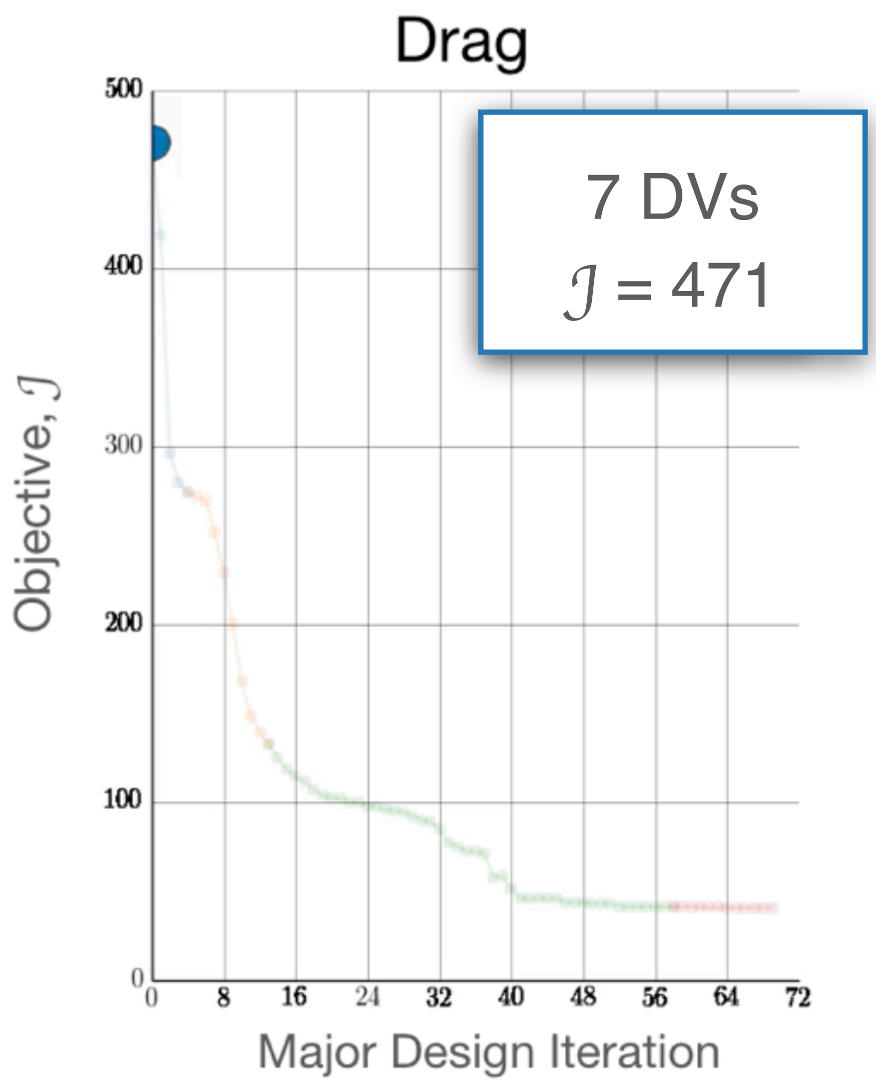
Good example since best parameterization is hard to predict

Results

Constrained transonic airfoil design

7 DVs - start of design



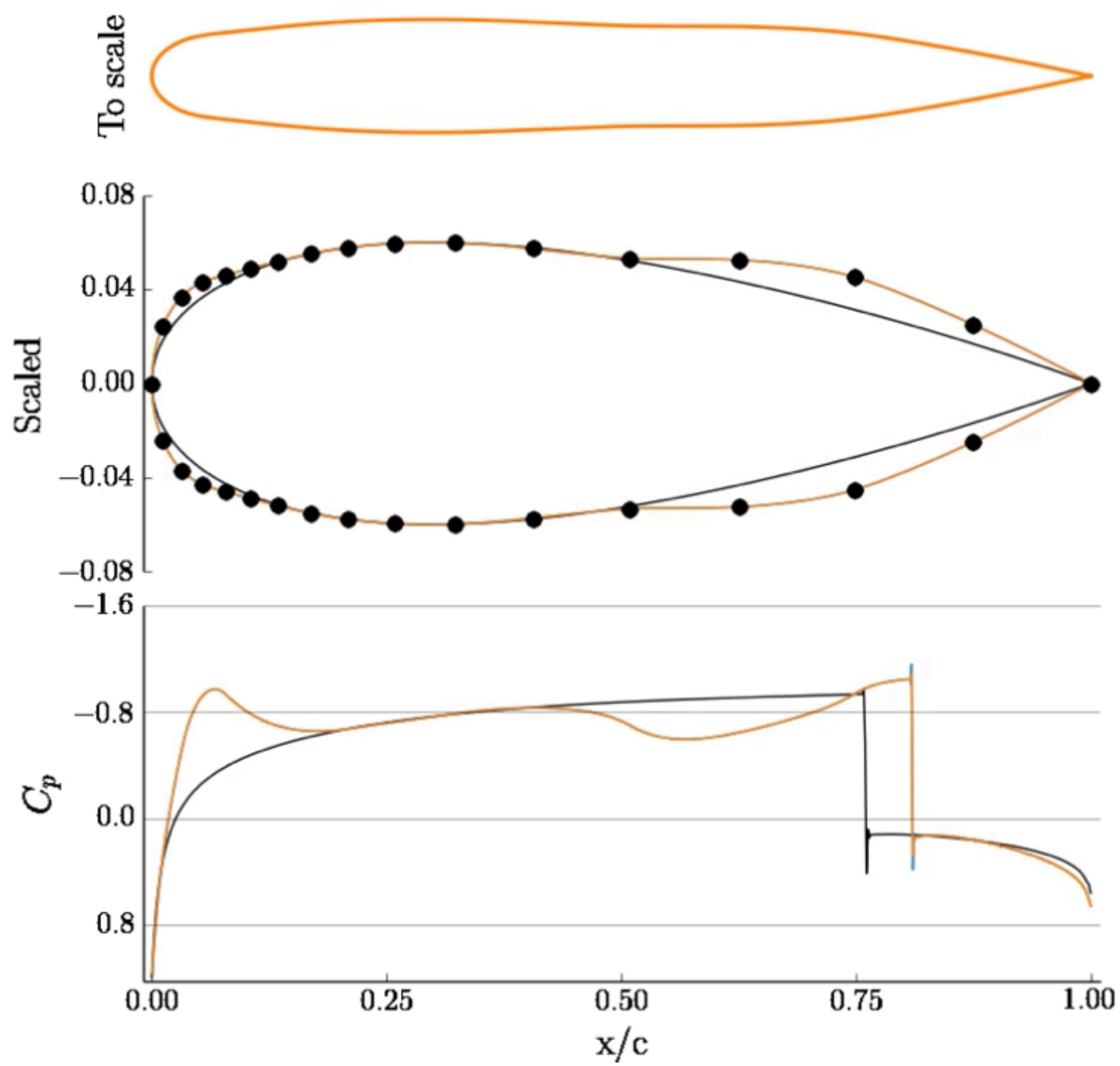


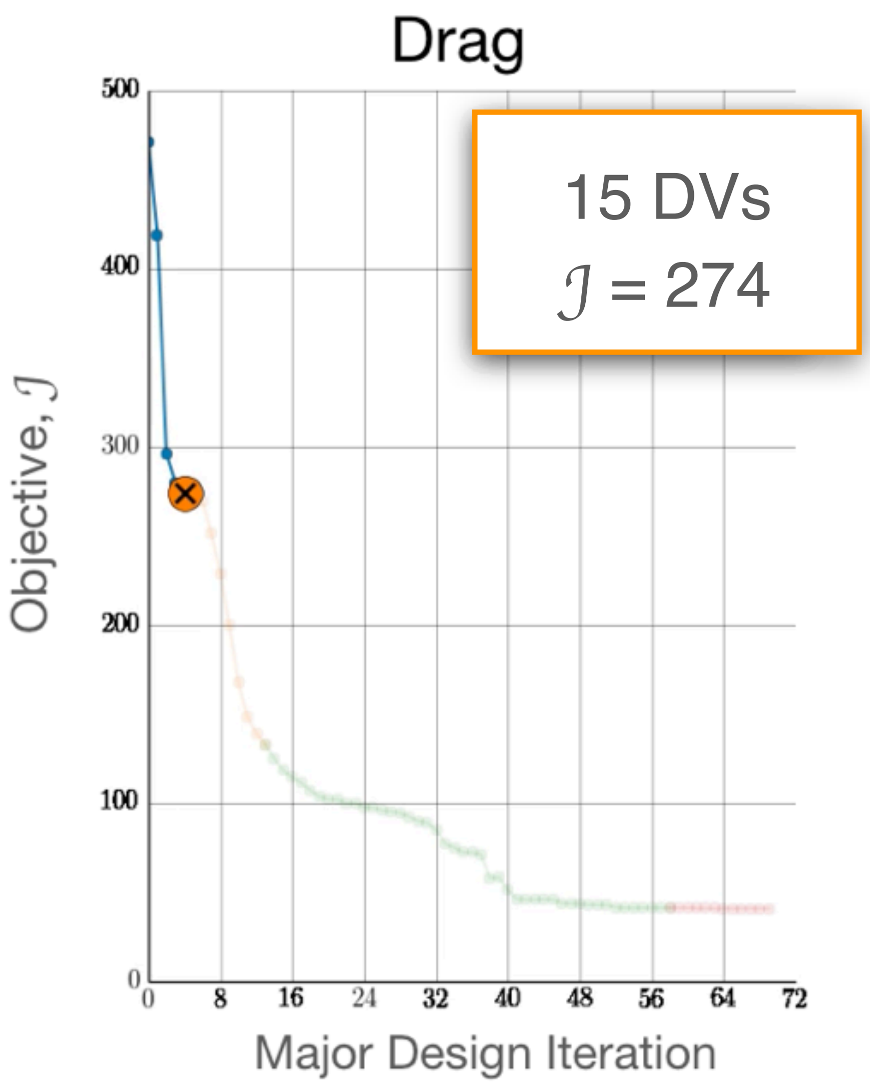
Initial Drag = 471 counts

Results

Constrained transonic airfoil design

15 DVs - 1 refinement

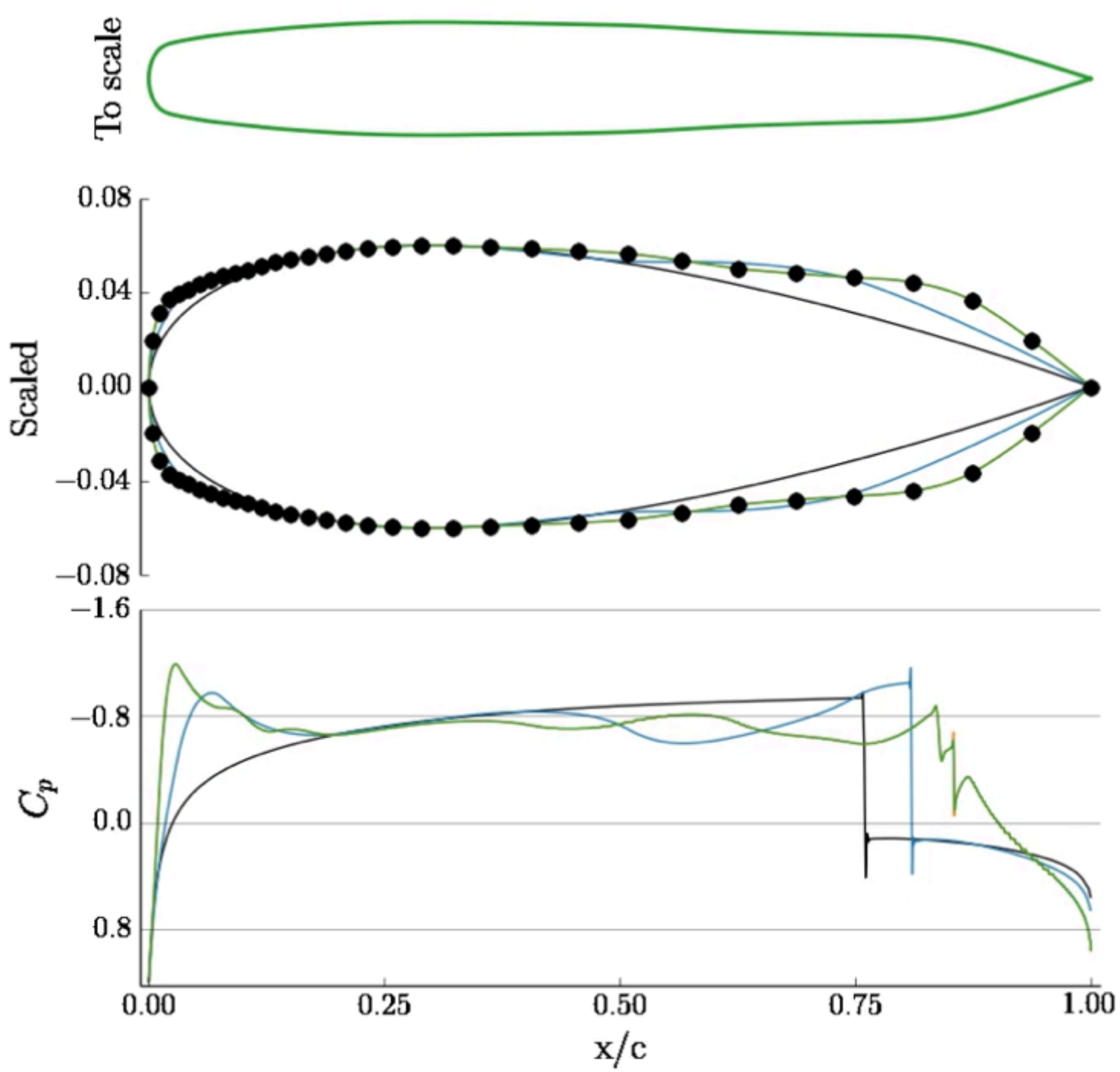


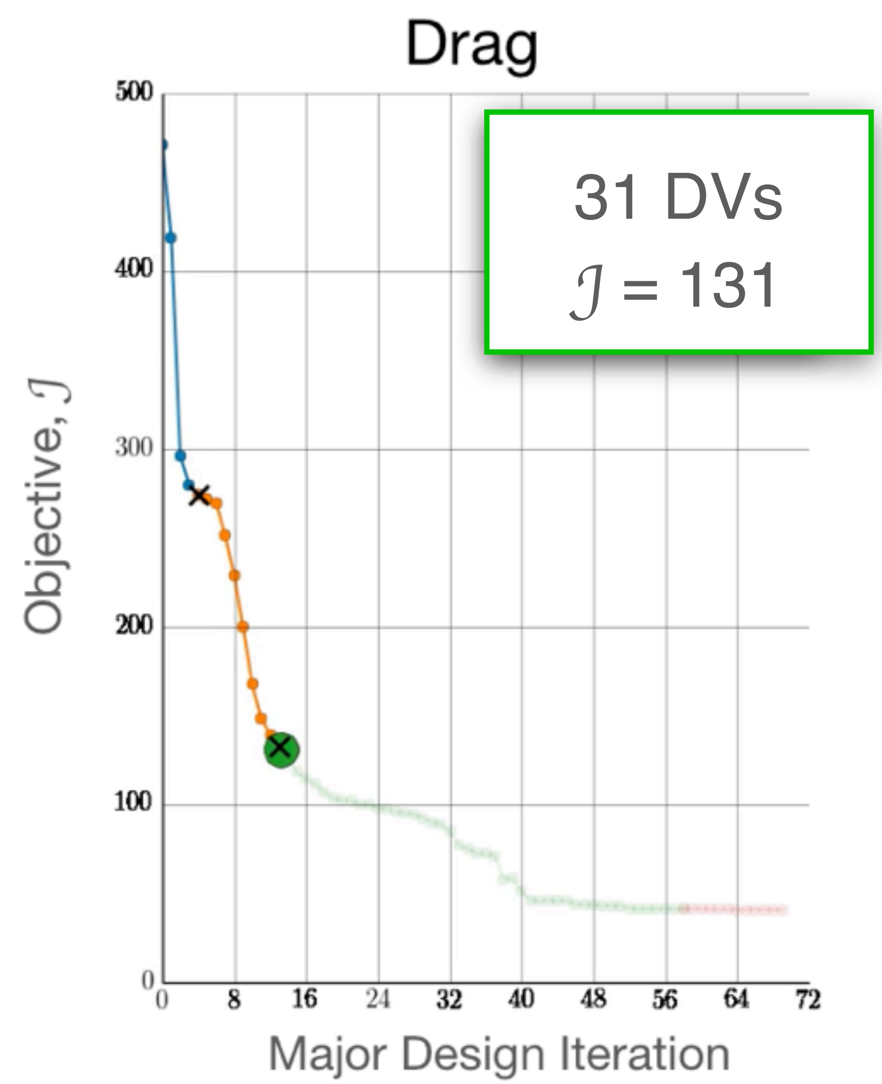


Results

Constrained transonic airfoil design

31 DVs - 2 refinements

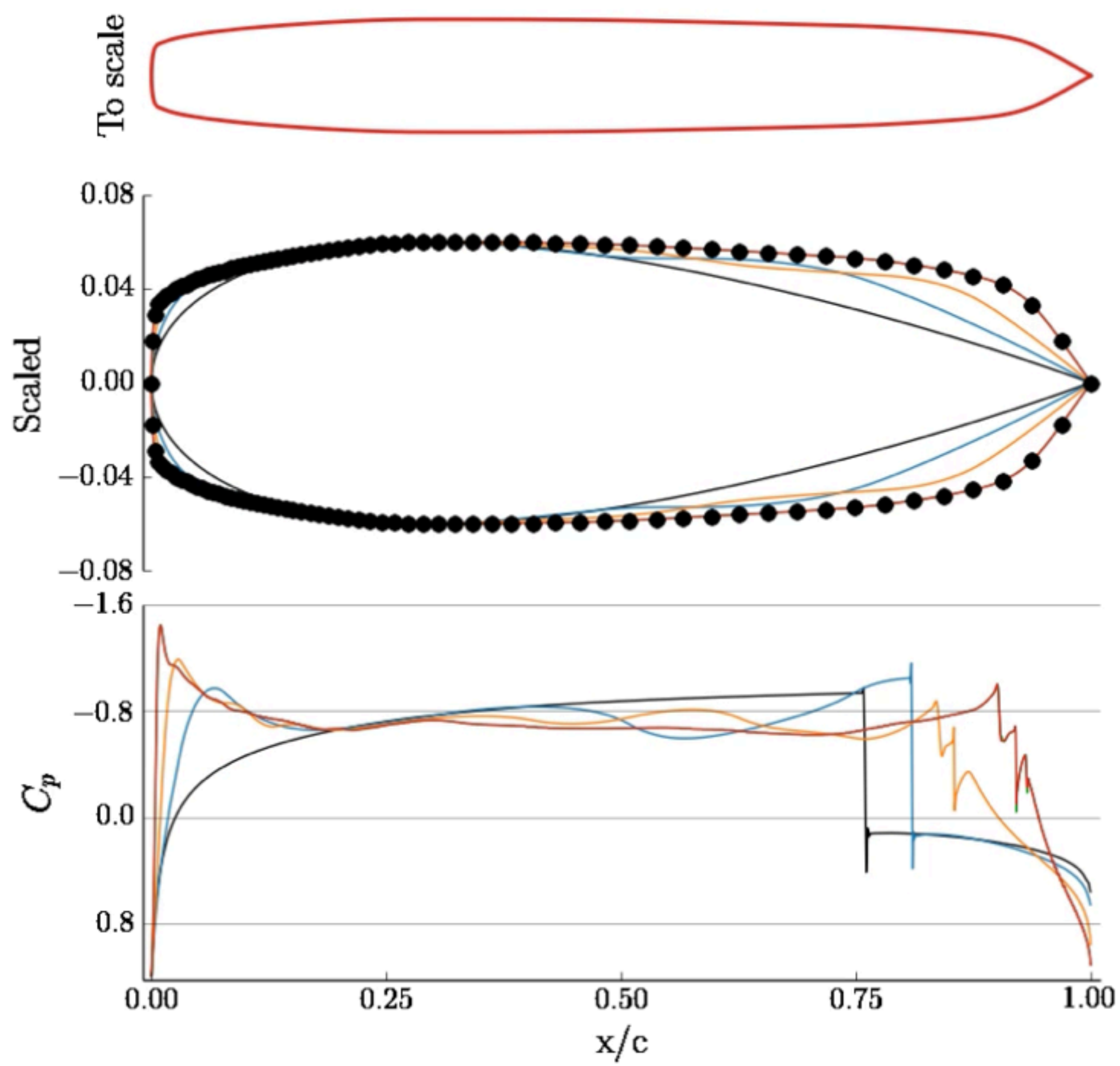


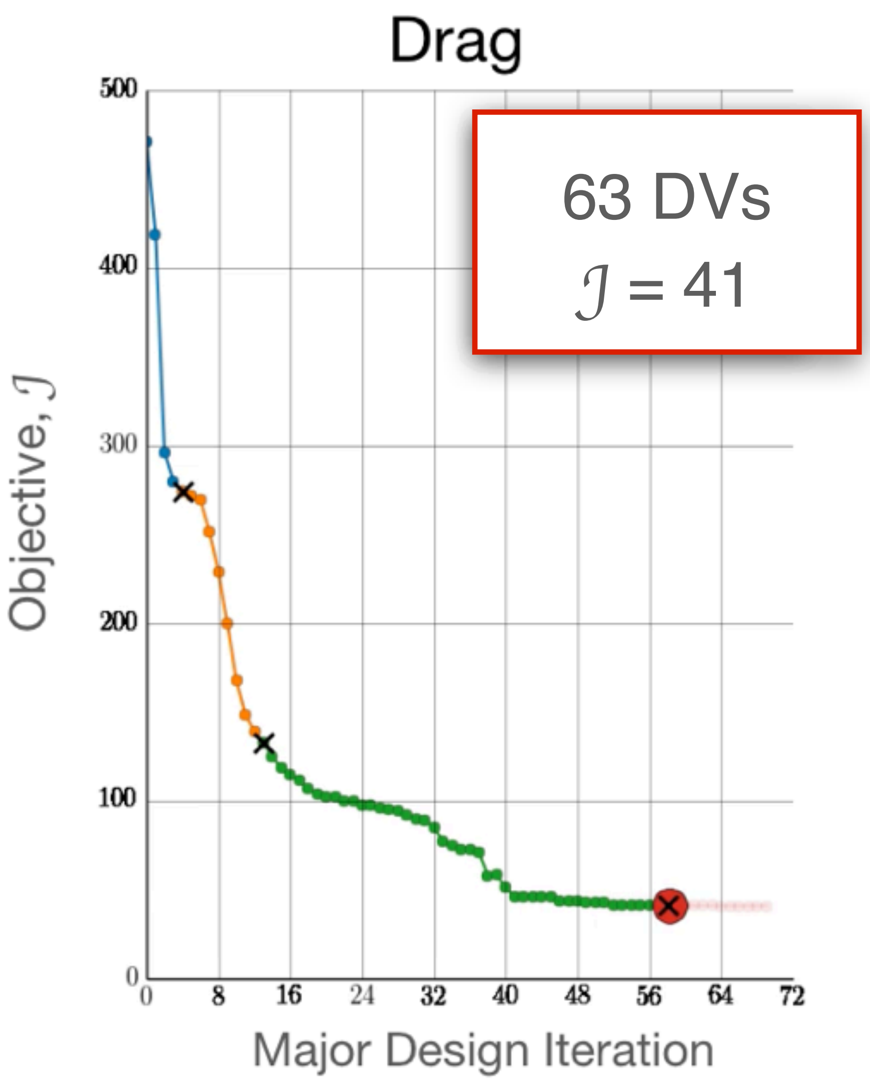


Results

Constrained transonic airfoil design

63 DVs - 3 refinements

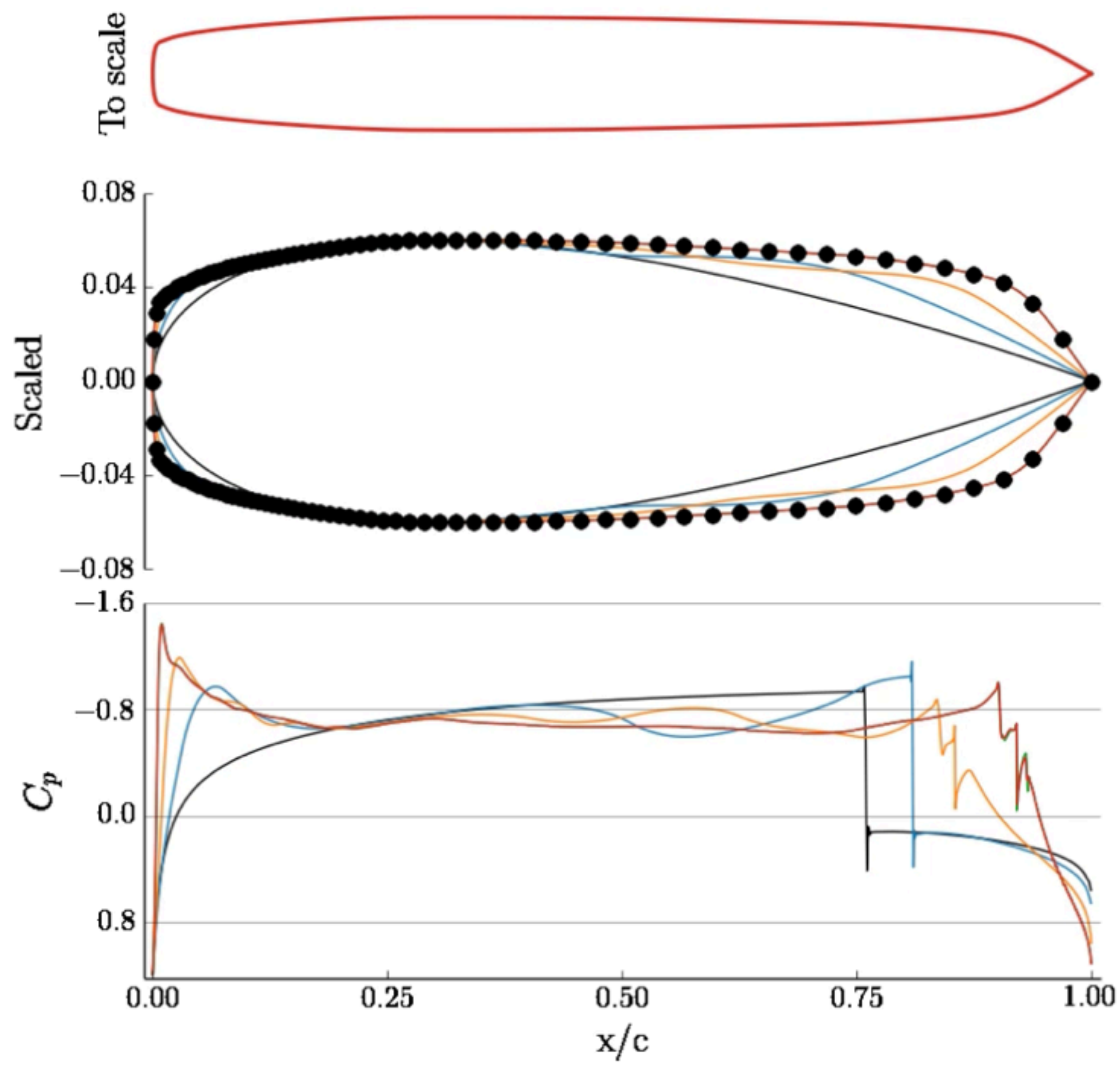


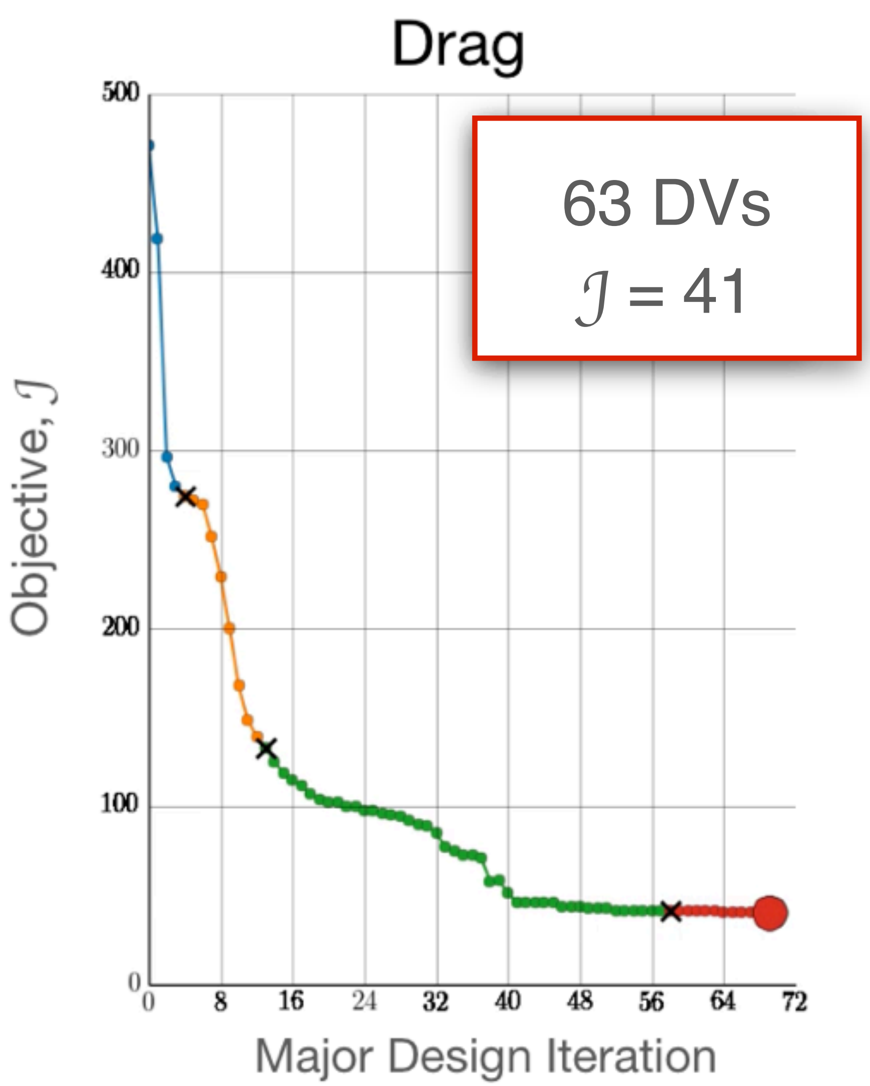


Results

Constrained transonic airfoil design

63 DVs - 3 refinements (final)



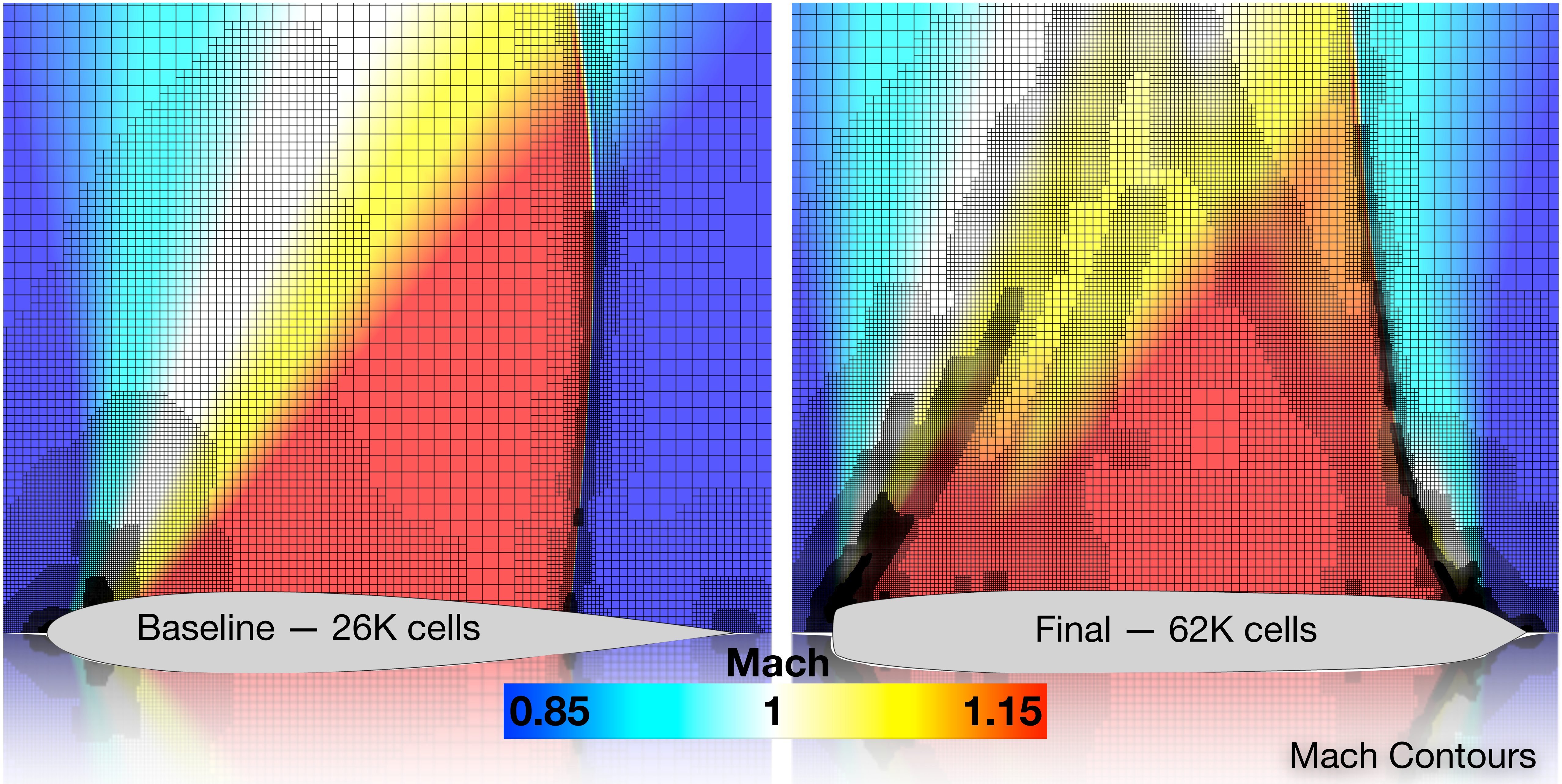


Final Drag = 41 counts

Results

Constrained transonic airfoil design

Error-control during optimization automatically refines grid as design improvement requires more fidelity

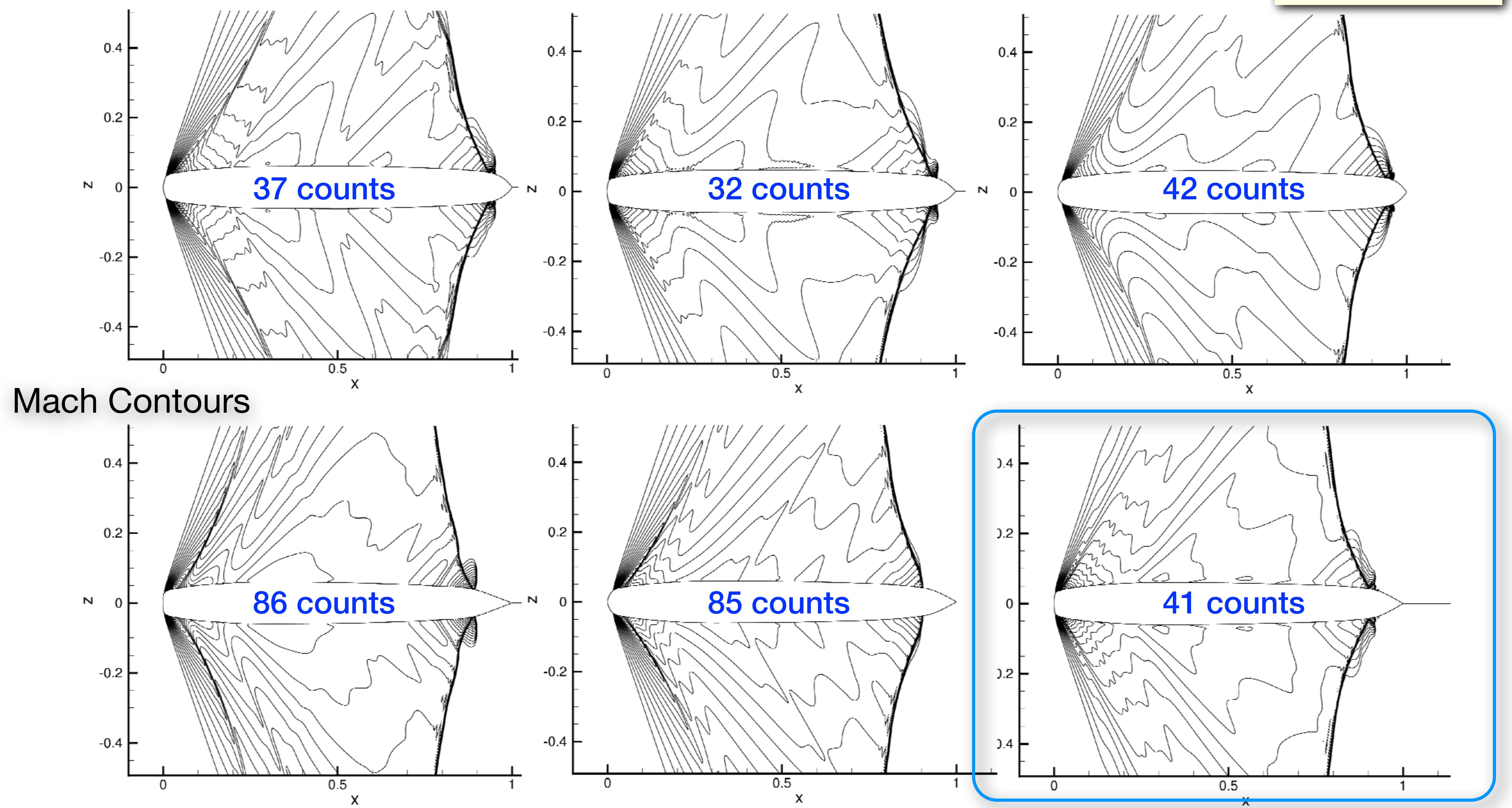


Results

Constrained transonic airfoil design

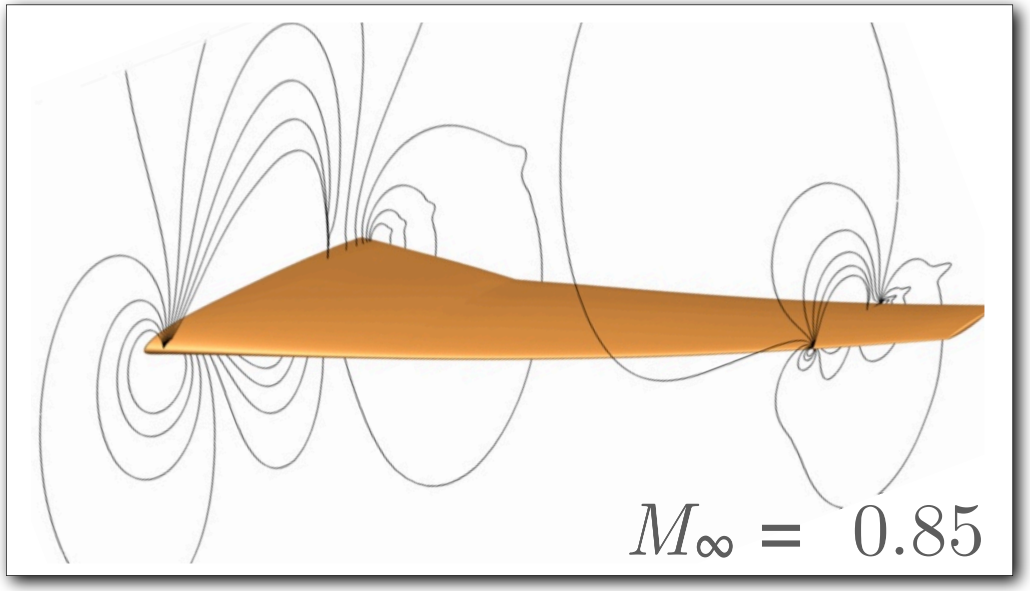
Workshop results from various participants

AIAA 2015-0263



Results

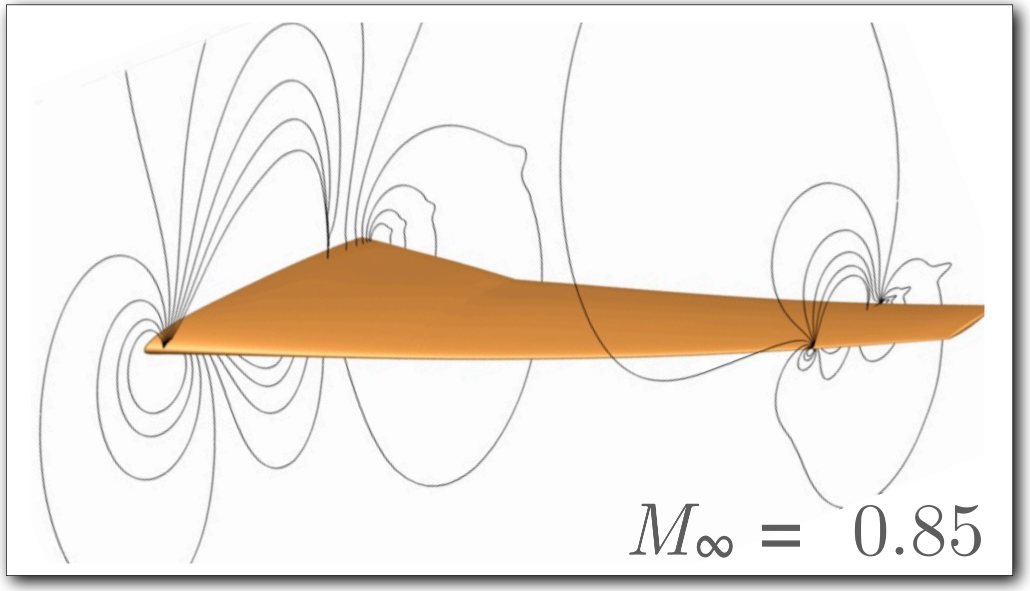
Constrained design of a 3D transonic wing



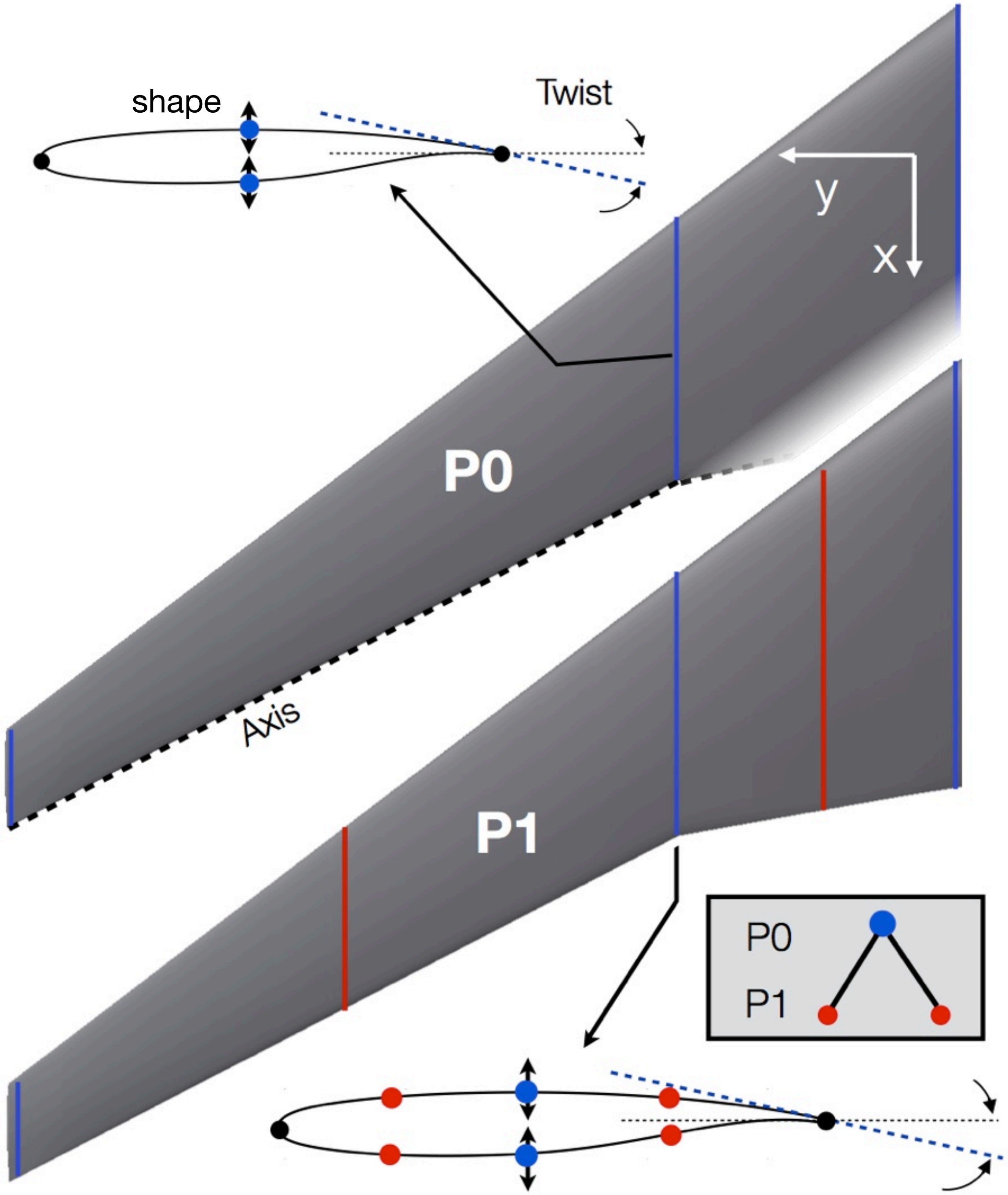
- Aero. Design Benchmarks, Prob. #4
- Objective: Minimize drag of CRM wing at $M_\infty = 0.85$
- Constraints: $C_L = 0.5$, $C_M \geq -0.17$, thickness & volume constraints

Results

Constrained design of a 3D transonic wing

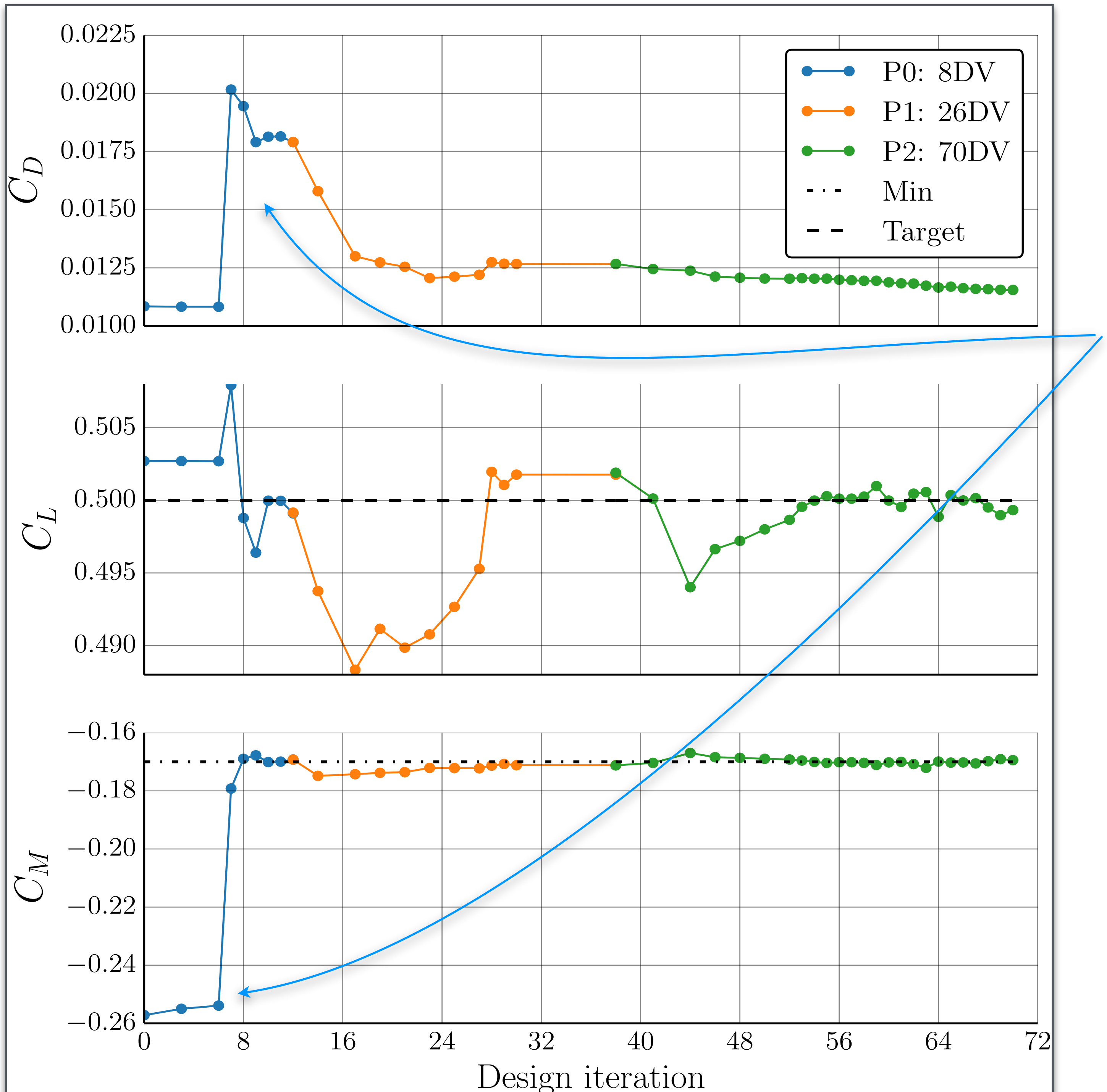


- Aero. Design Benchmarks, Prob. #4
- **Objective:** Minimize drag of CRM wing at $M_\infty = 0.85$
- **Constraints:** $C_L = 0.5$, $C_M \geq -0.17$, thickness & volume constraints
- **Parameterization:** Progressive for twist and airfoil shape: 9→21→71 DVs

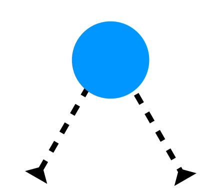


Results

Constrained design of a 3D transonic wing

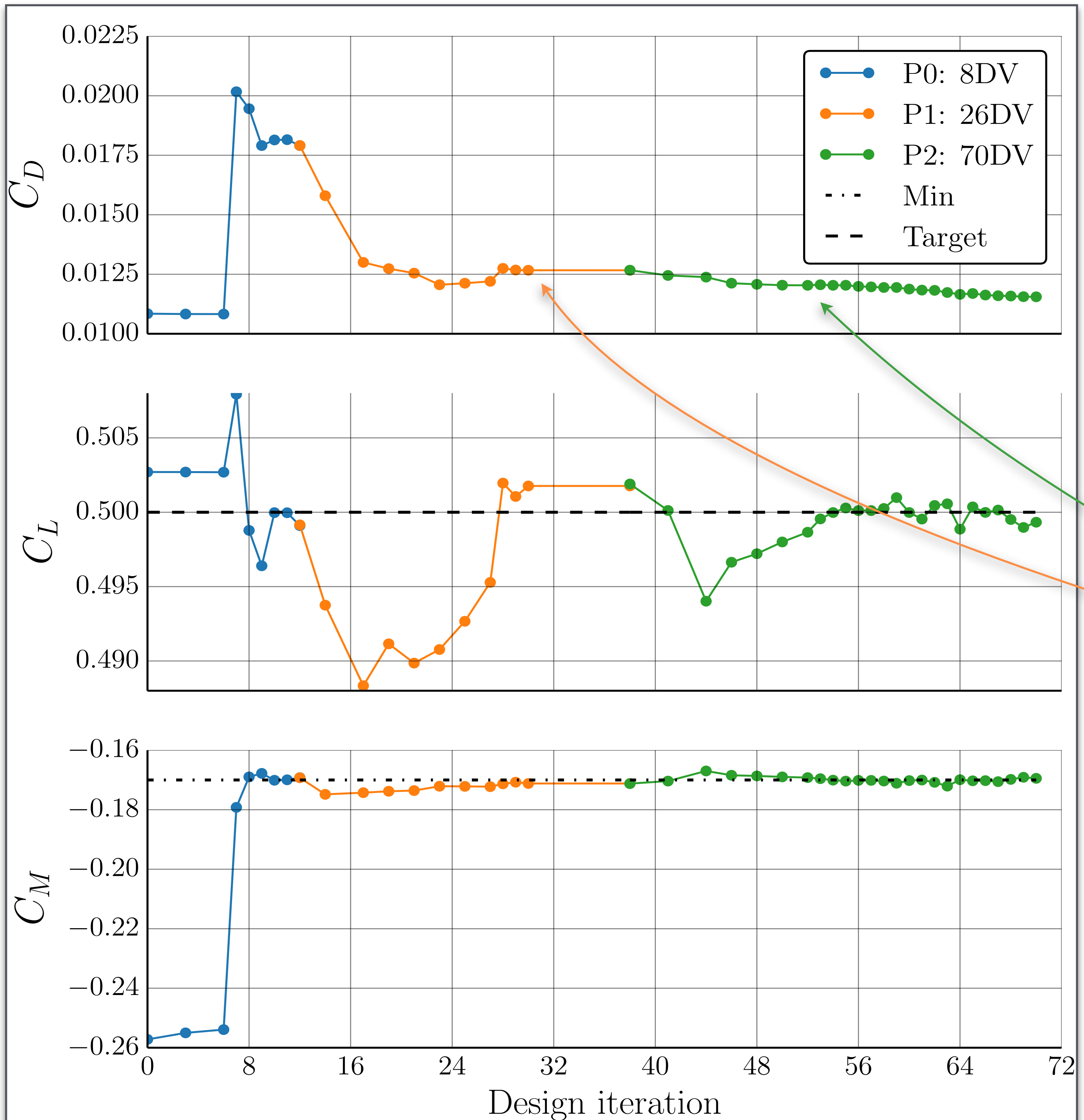


Under **P0**, pitching moment constraint is satisfied by sacrificing drag.



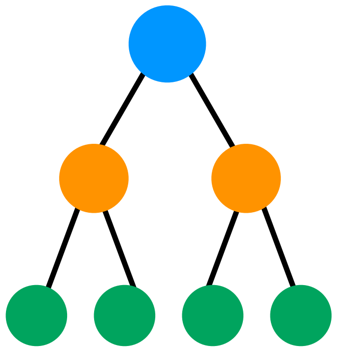
Results

Constrained design of a 3D transonic wing



Under **P0**, pitching moment constraint is satisfied by sacrificing drag.

P1, **P2** drive down drag while holding constraints.



Status

- Basic Blender plugins for I/O and shape manipulation

  Released to external users within ARC, LaRC and Industry – TRL 9

- Blender plugins supporting parametric markup for twist, skeletal, lattice & constraint-based deformation

  In use and beta-test within several ARMD Programs: CST & AATT – TRL 7

- Automatic parameter refinement (progressive refinement)

  Targeting beta-test by end of summer – TRL 6

- Adaptive parameter refinement (automatic, adaptive shape control)

  Final investigations in progress - completion by end of Phase II – TRL 5

Publications

- *Anderson, G.R., and Aftosmis, M.J., "Parametric Deformation of Discrete Geometry for Aerodynamic Shape Design". AIAA Paper 2012-0965, 50th AIAA ASM Meeting and Exhibit, Nashville, TN, January 2012.*
- *Anderson, G.R., Aftosmis, M.J., and Nemec, M., "Constraint-based Shape Parameterization for Aerodynamic Design". ICCFD7 Paper-2001. Seventh Inter- national Conference on Computational Fluid Dynamics (ICCFD7), Big Island, HI, July 2012.*
- *Rodriguez, D.L., Aftosmis, M.J., Nemec, M., and Smith, S.C., Static Aeroelastic Analysis with an Inviscid Cartesian Method. AIAA Paper 2014-0836, AIAA SciTech 2014, National Harbor MD, http://dx.doi.org/10.2514/6.2014-0836, January 2014.*
- *Anderson, G.R., Nemec, M., and Aftosmis, M. J., "Aerodynamic shape optimization benchmarks with error control and automatic parameterization." AIAA Paper 2015-1719, Kissimmee, FL, http://dx.doi.org/10.2514/6.2015-1719, January 2015.*
- *Rodriguez, D. L., Aftosmis, M.J., Nemec, M., and Anderson, G.R., "Optimized off-design performance of flexible wings with continuous trailing-edge flaps." AIAA Paper 2015–1409, AIAA SciTech 2015, Kissimmee, FL, http://dx.doi.org/10.2514/6.2014-1409, January 2015.*
- *Anderson, G. R., and Aftosmis, M. J., "Adaptive shape control for aerodynamic design." AIAA Paper 2015-0398, AIAA SciTech 2015, Kissimmee, FL, http://dx.doi.org/10.2514/6.2015-0398, January 2015.*

Thank You!

- Cartesian Methods Team

  David Rodriguez & Marian Nemec

- Beta users

  Mathias Wintzer (LaRC), Gulfstream & Boeing

- ARMD Seedling Fund & NASA Aeronautics Research Institute

  3 Years of outstanding support

Questions?

Michael Aftosmis

George Anderson